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Third Edition, Supplement No. 14
(Including Supplements 1-7)

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16. ABSTRACT

In this Supplement for AP-42, new or revised emissions data are presented for Anthracite Coal Combustion; Wood Waste Combustion In Boilers; Residential Fireplaces; Wood Stoves; Open Burning; Large Appliance Surface Coating; Metal Furniture Surface Coating; Adipic Acid; Synthetic Ammonia; Carbon Black; Charcoal; Explosives; Paint and Varnish; Phthalic Anhydride; Printing Ink; Soap and Detergents; Terephthalic Acid; Maleic Anhydride; Primary Aluminum Production; Iron and Steel Production; Gypsum Manufacturing; Construction Aggregate Processing; Sand and Gravel Processing; Taconite Ore Processing; Western Surface Coal Mining; Fugitive Dust Sources; Unpaved Roads; Agricultural Tilling; Aggregate Handling and Storage Piles; and Industrial Paved Roads.

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1.2 ANTHRACITE COAL COMBUSTION

1.2.1 General[1-2]

Anthracite coal is a high rank coal with a high fixed carbon content and low volatile matter content, relative to bituminous coal and lignite, and it has higher ignition and ash fusion temperatures. Because of its low volatile matter content and slight clinkering, anthracite is most commonly fired in medium sized traveling grate stokers and small hand fired units. Some anthracite (occasionally along with petroleum coke) is used in pulverized coal fired boilers. It is also blended with bituminous coal. None is fired in spreader stokers. Because of its low sulfur content (typically less than 0.8 weight percent) and minimal smoking tendencies, anthracite is considered a desirable fuel where readily available.

In the United States, all anthracite is mined in Northeastern Pennsylvania and is consumed mostly in Pennsylvania and several surrounding states. The largest use of anthracite is for space heating. Lesser amounts are employed for steam/electric production; coke manufacturing, sintering and pelletizing; and other industrial uses. Anthracite combustion currently is only a small fraction of the total quantity of coal combusted in the United States.

1.2.2 Emissions and Controls[2-14]

Particulate emissions from anthracite combustion are a function of furnace firing configuration, firing practices (boiler load, quantity and location of underfire air, sootblowing, flyash reinjection, etc.), and the ash content of the coal. Pulverized coal fired boilers emit the highest quantity of particulate per unit of fuel because they fire the anthracite in suspension, which results in a high percentage of ash carryover into the exhaust gases. Pulverized anthracite fired boilers operate in the dry tap or dry bottom mode because of anthracite's characteristically high ash fusion temperature. Traveling grate stokers and hand fired units produce much less particulate per unit of fuel fired, because combustion takes place in a quiescent fuel bed without significant ash carryover into the exhaust gases. In general, particulate emissions from traveling grate stokers will increase during sootblowing and flyash reinjection and with higher fuel bed underfeed air from forced draft fans. Smoking is rarely a problem because of anthracite's low volatile matter content.

Limited data are available on the emission of gaseous pollutants from anthracite combustion. It is assumed from bituminous coal combustion data that a large fraction of the fuel sulfur is emitted as sulfur oxides. Also, because combustion equipment, excess air rates, combustion temperatures, etc., are similar between anthracite and bituminous coal combustion, nitrogen oxide and carbon monoxide emissions are assumed to be similar, too. Volatile organic compound (VOC) emissions, however, are expected to be considerably lower because the volatile matter content of anthracite is significantly less than that of bituminous coal.

TABLE 1.2-1. UNCONTROLLED EMISSION FACTORS FOR ANTHRACITE COMBUSTION[a]

Boiler Type	Particulates[b]		Sulfur Oxides[c]		Nitrogen Oxides[d]		Carbon Monoxide[e]		VOC	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	Nonmethane	Methane
Pulverized coal fired	f	f	19.5S	39S	9	18	f	f	f	f
Traveling grate stoker	4.6[g]	9.1[g]	19.5S	39S	5	10	0.3	0.6	f	f
Hand fed units	5[h]	10[h]	19.5S	39S	1.5	3	f	f	f	f

[a] Factors are for uncontrolled emissions and should be applied to coal consumption as fired.

[b] Based on EPA Method 5 (front half catch).

[c] Based on the assumption that, as with bituminous coal combustion, most of the fuel sulfur is emitted as sulfur oxides. Limited data in Reference 5 verify this assumption for pulverized anthracite fired boilers. Most of these emissions are SO_2, with 1 - 3% SO_3. S indicates that the weight percent of sulfur in the oil should be multiplied by the value given.

[d] For pulverized anthracite fired boilers and hand fed units, assumed to be similar to bituminous coal combustion. For traveling grate stokers, see References 8 and 11.

[e] May increase by several orders of magnitude if a boiler is not properly operated or maintained. Factors for traveling grate stokers are based on limited information in Reference 8. Factors for pulverized coal fired boilers substantiated by additional data in Reference 14.

[f] Emission factor reported in Table 1.1-1 may be used, based on the similarity of anthracite and bituminous coal.

[g] References 12-13, 15-18. Accounts for limited fallout that may occur in fallout chambers and stack breeching. Emission factors for individual boilers may range from 2.5 - 25 kg/Mg (5 - 50 lb/ton) and as high as 25 kg/Mg (50 lb/ton) during sootblowing.

[h] Reference 2.

Control of emissions from anthracite combustion has mainly been limited to particulate matter. The most efficient particulate controls - fabric filters, scrubbers and electrostatic precipitators - have been installed on large pulverized anthracite fired boilers. Fabric filters and venturi scrubbers can effect collection efficiencies exceeding 99 percent. Electrostatic precipitators, on the other hand, are typically only 90 to 97 percent efficient, because of the characteristic high resistivity of low sulfur anthracite flyash. It is reported that higher efficiencies can be achieved using larger precipitators and flue gas conditioning. Mechanical collectors are frequently employed upstream from these devices for large particle removal.

Traveling grate stokers are often uncontrolled. Indeed, particulate control has often been considered unnecessary because of anthracite's low smoking tendencies and of the fact that a significant fraction of large size flyash from stokers is readily collected in flyash hoppers as well as in the breeching and base of the stack. Cyclone collectors have been employed on traveling grate stokers, and limited information suggests these devices may be up to 75 percent efficient on particulate. Flyash reinjection, frequently used in traveling grate stokers to enhance fuel use efficiency, tends to increase particulate emissions per unit of fuel combusted.

Emission factors for anthracite combustion are presented in Table 1.2.1, and emission factor ratings in Table 1.2-2.

TABLE 1.2-2. ANTHRACITE COAL EMISSION FACTOR RATING[a]

Furnace Type	Particulates	Sulfur Oxides	Nitrogen Oxides	Carbon Monoxide	VOC Nonmethane	 Methane
Pulverized coal	B	B	B	B	C	C
Traveling grate	B	B	B	B	C	C
Hand fed units	B	B	B	B	D	D

[a] The emission factor rating is explained in the Introduction to this volume.

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17. Source Sampling of Anthracite Coal Fired Boilers, Pennhurst Center, Spring City, Pennsylvania, Final Report, TRC Environmental Consultants, Inc., Wethersfield, CT, January 23, 1980.

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TABLE 1.6-1. EMISSION FACTORS FOR WOOD AND BARK COMBUSTION IN BOILERS

Pollutant/Fuel Type	kg/Mg	lb/ton	Emission Factor Rating
Particulate[a,b]			
Bark[c]			
Multiclone, with flyash reinjection[d]	7	14	B
Multiclone, without flyash reinjection[d]	4.5	9	B
Uncontrolled	24	47	B
Wood/bark mixture[e]			
Multiclone, with flyash reinjection[d,f]	3	6	C
Multiclone, without flyash reinjection[d,f]	2.7	5.3	C
Uncontrolled[g]	3.6	7.2	C
Wood[h]			
Uncontrolled	4.4	8.8	C
Sulfur Dioxide[i]	0.075 (0.01 - 0.2)	0.15 (0.02 - 0.4)	B
Nitrogen Oxides (as NO_2)[j]			
50,000 - 400,000 lb steam/hr	1.4	2.8	B
<50,000 lb steam/hr	0.34	0.68	B
Carbon Monoxide[k]	2-24	4-47	C
VOC			
Nonmethane[l]	0.7	1.4	D
Methane[m]	0.15	0.3	E

[a] References 2,4,9,17-18. For boilers burning gas or oil as an auxiliary fuel, all particulates are assumed to result from only wood waste fuel.

[b] May include condensible hydrocarbons consisting of pitches and tars, mostly from back half catch of EPA Method 5. Tests reported in Reference 20 indicate that condensible hydrocarbons account for 4% of total particulate weight.

[c] Based on fuel moisture content of about 50%.

[d] After control equipment, assuming an average collection efficiency of 80%. Data from References 4, 7 and 8 indicate that 50% flyash reinjection increases the dust load at the cyclone inlet 1.2 to 1.5 times, while 100% flyash reinjection increases the load 1.5 to 2 times the load without reinjection.

[e] Based on fuel moisture content of 33%.

[f] Based on large dutch ovens and spreader stokers (averaging 23,430 kg steam/hr) with steam pressures from 20 - 75 kpa (140 - 530 PSI).

[g] Based on small dutch ovens and spreader stokers (usually operating <9075 kg steam/hr), with pressures from 5 - 30 kpa (35 - 230 PSI). Careful air adjustments and improved fuel separation and firing were used on some units, but the effects cannot be isolated.

[h] References 12-13, 19, 27. Wood waste includes cuttings, shavings, sawdust and chips, but not bark. Moisture content ranges from 3 - 50% by weight. Based on small units (<3000 kg steam/hr) in New York and North Carolina.

[i] Reference 23. Based on tests of fuel sulfur content and sulfur dioxide emissions at four mills burning bark. The lower limit of the range (in parentheses) should be used for wood, and higher values for bark. A heating value of 5000 kcal/kg (9000 BTU/lb) is assumed. The factors are based on the dry weight of fuel.

[j] References 7, 24-26. Several factors can influence emission rates, including combustion zone, temperatures, excess air, boiler operating conditions, fuel moisture and fuel nitrogen content.

[k] Reference 30.

[l] References 20, 30. Nonmethane VOC reportedly consists of compounds with a high vapor pressure such as alpha pinene.

[m] Reference 30. Based on an approximation of methane/nonmethane ratio, which is very variable. Methane, expressed as a percent of total volatile organic compounds, varied from 0 - 74 weight %.

a tenfold increase in the dust loadings of some systems, although increases of 1.2 to 2 times are more typical for boilers using 50 to 100 percent reinjection. A major factor affecting this dust loading increase is the extent to which the sand and other noncombustibles can successfully be separated from the flyash before reinjection to the furnace.

Although reinjection increases boiler efficiency from 1 to 4 percent and minimizes the emissions of uncombusted carbon, it also increases boiler maintenance requirements, decreases average flyash particle size and makes collection more difficult. Properly designed reinjection systems should separate sand and char from the exhaust gases, to reinject the larger carbon particles to the furnace and to divert the fine sand particles to the ash disposal system.

Several factors can influence emissions, such as boiler size and type, design features, age, load factors, wood species and operating procedures. In addition, wood is often cofired with other fuels. The effect of these factors on emissions is difficult to quantify. It is best to refer to the references for further information.

The use of multitube cyclone mechanical collectors provides the particulate control for many hogged boilers. Usually, two multicyclones are used in series, allowing the first collector to remove the bulk of the dust and the second collector to remove smaller particles. The collection efficiency for this arrangement is from 65 to 95 percent. Low pressure drop scrubbers and fabric filters have been used extensively for many years. On the West Coast, pulse jets have been used.

Emission factors for wood waste boilers are presented in Table 1.6-1.

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1.9 RESIDENTIAL FIREPLACES

1.9.1 General[1-2]

Fireplaces are used mainly in homes, lodges, etc., for supplemental heating and for aesthetic effects. Wood is the most common fuel for fireplaces, but, coal, compacted wood waste "logs", paper and rubbish may also be burned. Fuel is intermittently added to the fire by hand.

Fireplaces can be divided into two broad categories, 1) masonry, generally brick fireplaces, assembled on site integral to a structure and 2) prefabricated, usually metal, fireplaces installed on site as a package with appropriate ductwork.

Masonry fireplaces typically have large fixed openings to the firebed and dampers above the combustion area in the chimney to limit room air and heat losses when the fireplace is not being used. Some masonry fireplaces are designed or retrofitted with doors and louvers to reduce the intake of combustion air during use.

Many varieties of prefabricated fireplaces are now available on the market. One general class is the freestanding fireplace. The most common freestanding fireplace models consist of an inverted sheet metal funnel and stovepipe directly above the fire bed. Another class is the "zero clearance" fireplace, an iron or heavy gauge steel firebox lined with firebrick on the inside and surrounded by multiple steel walls spaced for air circulation. Zero clearance fireplaces can be inserted into existing masonry fireplace openings, thus they are sometimes called "inserts". Some of these units are equipped with close fitting doors and have operating and combustion characteristics similar to wood stoves (see Section 1.10, Residential Wood Stoves). Prefabricated fireplaces are commonly equipped with louvers and glass doors to reduce the intake of combustion air, and some are surrounded by ducts through which floor level air is drawn by natural convection and is heated and returned to the room.

Masonry fireplaces usually heat a room by radiation, with a significant fraction of the combustion heat lost in the exhaust gases or through the fireplace walls. Moreover, some of the radiant heat entering the room must go toward warming the air that is pulled into the residence to make up for the air drawn up the chimney. The net effect is that masonry fireplaces are usually inefficient heating devices. Indeed, in cases where combustion is poor, where the outside air is cold, or where the fire is allowed to smolder (thus drawing air into a residence without producing appreciable radiant heat energy), a net heat loss may occur in a residence from use of a fireplace. Fireplace heating efficiency may be improved by a number of measures that either reduce the excess air rate or transfer some of the heat back into the residence that would normally be lost in the exhaust gases or through the fireplace walls. As noted above, such measures are commonly incorporated into prefabricated units. As a result, the energy efficiencies of prefabricated fireplaces are slightly higher than those of masonry fireplaces.

1.9.2 Emissions[3-10]

The major pollutants of concern from fireplaces are unburnt combustibles, including carbon monoxide, gaseous organics and particulate matter (i.e., smoke). Significant quantities of unburnt combustibles are produced because fireplaces are inefficient combustion devices, because of high uncontrolled excess air rates and the absence of any sort of secondary combustion. The latter is especially important in wood burning because of its high volatile matter content, typically 80 percent on a dry weight basis. In additon to unburnt combustibles, lesser amounts of nitrogen oxides and sulfur oxides are emitted.

Polycyclic organic material (POM), a minor but potentially important component of wood smoke, is a group of organic compounds which includes potential carcinogens such as benzo(a)pyrene (BaP). POM results from the combination of free radical species formed in the flame zone, primarily as a consequence of incomplete combustion. Under reducing conditions, radical chain propagation is enhanced, allowing the buildup of complex organic material such as POM. POM is generally found in or on smoke particles, although some sublimation into the vapor phase is probable.

Another important constituent of wood smoke is creosote. This tar-like substance will burn if the fire is sufficiently hot, but at lower temperatures, it may deposit on cool surfaces in the exhaust system. Creosote deposits are a fire hazard in the flue, but they can be reduced if the exhaust ductwork is insulated to prevent creosote condensation or the exhaust system is cleaned regularly to remove any buildup.

Fireplace emissions are highly variable and are a function of many wood characteristics and operating practices. In general, conditions which promote a fast burn rate and a higher flame intensity will enhance secondary combustion and thereby lower emissions. Conversely, higher emissions will result from a slow burn rate and a lower flame intensity. Such generalizations apply particularly to the earlier stages of the burning cycle, when significant quantities of combustible volatile matter are being driven out of the wood. Later in the burning cycle, when all of the volatile matter has been driven out of the wood, the charcoal that remains burns with relatively few emissions.

Emission factors and corresponding factor ratings for wood combustion in residential fireplaces are given in Table 1.9-1.

TABLE 1.9-1. EMISSION FACTORS FOR RESIDENTIAL FIREPLACES

Pollutant	Wood[a]		Emission Factor Ratings
	g/kg	lb/ton	
Particulate[b]	14	28	C
Sulfur oxides[c]	0.2	0.4	A
Nitrogen oxides[d]	1.7	3.4	C
Carbon monoxide[e]	85	170	C
VOC[f]			
Methane	-	-	
Nonmethane	13	26	D

[a] Based on tests burning primarily oak, fir or pine, with moisture content ranging from 15 - 35%.

[b] References 1, 3-4, 8-10. Includes condensible organics (back half catch of EPA Method 5 or similar test method), which alone accounts for 54 - 76% of the total mass collected by both the front and back half catches (Reference 4). POM is carried by suspended particulate matter and has been found to range from 0.017 - 0.044 g/kg (References 1, 4) which may include BaP of up to 1.7 mg/kg (Reference 1).

[c] References 2, 4.

[d] Expressed as NO_2. References 3-4, 8, 10.

[e] References 1, 3-4, 6, 8-10.

[f] References 1, 3-4, 6, 10. Dash = no data available.

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1.10 RESIDENTIAL WOOD STOVES

1.10.1 General[1-2]

Wood stoves are used primarily as domestic space heaters to supplement conventional heating systems. The two basic designs for wood stoves are radiating and circulating. Common construction materials include cast iron, heavy gauge sheet metal and stainless steel. Radiating type stoves transfer heat to the room by radiation from the hot stove walls. Circulating type stoves have double wall construction with louvers on the exterior wall to permit the conversion of radiant energy to warm convection air. Properly designed, these stoves range in heating efficiency from 50 to 70 percent. Radiant stoves have proven to be somewhat more efficient than the circulating type.

The thoroughness of combustion and the amount of heat transferred from a stove, regardless of whether it is a radiating or circulatory model, depend heavily on firebox temperature, residence time and turbulence (mixing). The "three Ts" (temperature, time and turbulence) are affected by air flow patterns through the stove and by the mode of stove operation. Many stove designs have internal baffles that increase the residence time of flue gases, thus promoting heat transfer. The use of baffles and secondary combustion air may also help to reduce emissions by promoting mixing and more thorough combustion. Unless the secondary air is adequately preheated, it may serve to quench the flue gas, thus retarding, rather than enhancing, secondary combustion. Secondary combustion air systems should be designed to deliver the proper amount of secondary air at the right location with adequate turbulence and sufficient temperature to promote true secondary combustion.

Stoves are further categorized by the air flow pattern through the burning wood within the stoves. Example generic designs - updraft, downdraft, crossdraft and "S-flow" - are shown schematically in Figure 1.10-1.

In the updraft air flow type of stove, air enters at the base of the stove and passes through the wood to the stovepipe at the top. Secondary air enters above the wood to assist in igniting unburned volatiles in the combustion gases. Updraft stoves provide very little gas phase residence time, which is needed for efficient transfer of heat from the gases to the walls of the stove and/or stovepipe.

The downdraft air flow type of stove initially behaves like an updraft. A vertical damper is opened at the top rear to promote rapid combustion. When a hot bed of coals is developed, the damper is closed, and the flue gases are then forced back down through the bed of coals before going out the flue exit.

The side or cross draft is equipped with a vertical baffle (open at the bottom) and an adjustable damper at the top, similar to the downdraft. The damper is open when combustion is initiated, to generate hot coals and adequate draft. The damper is then closed. The gases must then move down

25

under the vertical baffle, the flame is developed horizontally to the fuel bed, and ideally the gases and flame come in contact at the baffle point before passing out the flue exit.

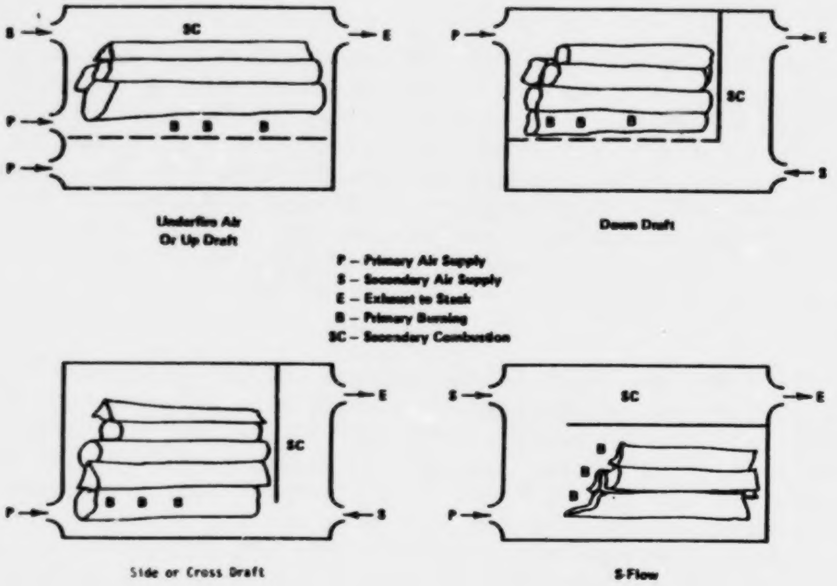

Figure 1.10-1. Generic designs of wood stoves based on flow paths

The S-flow, or horizontal baffle, stove is equipped with both a primary and a secondary air inlet, like the updraft stove. Retention time within the stove is a function of both the rate of burn and the length of the smoke path. To lengthen the retention time, gases are kept from exiting directly up the flue by a metal baffle plate located several inches above the burning wood. The baffle plate absorbs a considerable amount of heat and reflects and radiates much of it back to the firebox. The longer gas phase residence time results in improved combustion when the proper amounts of air are provided, and it enhances heat transfer from the gas phase.

Softwoods and hardwoods are the most common fuels for residential stoves. Coal and waste fuels, which burn at significantly higher temperature than cordwood, are not included in computing emission factors because of the relative scarcity of test data available. The performance of various heaters within a given type will vary, depending on how a particular design uses its potential performance advantages. Much of the available emissions data came from studies conducted on stoves designed for woodburning.

1.10.2 Emissions and Controls[3-25]

Residential combustion of wood produces atmospheric emissions of particulates, sulfur oxides, nitrogen oxides, carbon monoxide, organic materials including polycyclic organic matter (POM), and mineral constituents. Organic species, carbon monoxide and, to a large extent, the particulate matter emissions result from incomplete combustion of the fuel. Efficient combustion tends to limit emissions of carbon monoxide and volatile organic compounds by oxidizing these compounds to carbon dioxide and water. Sulfur oxides arise from oxidation of fuel sulfur, while nitrogen oxides are formed both from fuel nitrogen and by the combination of atmospheric nitrogen with oxygen in the combustion zone. Mineral constituents in the particulate emissions result from minerals released from the wood matrix during combustion and entrained in the combustion gases.

Wood smoke is composed of unburned fuel - combustible gases, droplets and solid particulates. Part of the organic compounds in smoke often condenses in the chimney or flue pipe. This tar-like substance is called creosote. If the combustion zone temperature is sufficiently high, creosote burns with the other organic compounds in the wood. However, creosote burns at a higher temperature than other chemicals in the wood, so there are times when it is not burned with the other products. Creosote deposits are a fire hazard, but they can be reduced if the exhaust ductwork is insulated to prevent creosote condensation, or the exhaust system is cleaned regularly to remove any buildup.

Polycyclic organic material (POM), a minor but potentially important component of wood smoke, is a group of organic compounds which includes potential carcinogens such as benzo(a)pyrene (BaP). POM results from the combination of free radical species formed in the flame zone, primarily as a consequence of incomplete combustion. Under reducing conditions, radical chain propagation is enhanced, allowing the buildup of complex organic material such as POM. POM is generally found in or on smoke particles, although some sublimation into the vapor phase is probable.

Emissions from any one stove are highly variable, and they correspond directly to different stages in the burning cycle. A new charge of wood produces a quick drop in firebox temperature and a dramatic increase in emissions, primarily organic matter. When all of the volatiles have been driven off, the charcoal stage of the burn is characterized by relatively clean emissions.

Emissions of particulate, carbon monoxide and volatile organic compounds were found to depend on burn rate. Emissions increase as burn rates decrease, for the great majority of the closed combustion devices currently on the market. A burn rate of approximately three kilograms per hour has been determined representative of actual woodstove operation.

Wood is a complex fuel, and the combined processes of combustion and pyrolysis which occur in a wood heater are affected by changes in the composition of the fuel, moisture content and the effective burning surface area. The moisture content of wood depends on the type of wood and the amount of time it has been dried (seasoned). The water in the wood increases the amount of heat required to raise the wood to its combustion point, thus reducing the rate of pyrolysis until moisture is released. Wood moisture has been found to have little affect on emissions. Dry wood (less than 15 percent moisture content) may produce slightly higher emissions than the commonly occurring 30 to 40 percent moisture wood. However, firing very wet wood may produce higher emissions due to smoldering and reduced burn rate. The size of the wood also has a large effect on the rate of pyrolysis. For smaller pieces of wood, there is a shorter distance for the pyrolysis products to diffuse, a larger surface area-to-mass ratio, and a reduction in the time required to heat the entire piece of wood. One effect of log size is to change the distribution of organics among the different effluents (creosote, particulate matter and condensible organics) for a given burn rate. These results also indicate that the distribution of the total organic effluent among creosote, particulate matter and condensibles is a function of firebox and sample probe temperatures.

Results of ultimate analysis (for carbon, hydrogen and oxygen) of dry wood types are within one to two percent for the majority of all species. The inherent difference between softwood and hardwood is the greater amount of resins in softwoods, which increases their heating value by weight.

Several combustion modification techniques are available to reduce emissions from wood stoves, with varying degrees of effectiveness. Some techniques relate to modified stove design and others to operator practices. Proper modifications of stove design (1) will reduce pollutant formation in the fuel magazine or in the primary combustion zone or (2) will cause previously formed emissions to be destroyed in the primary or secondary combustion zones.

A recent wood stove emission control development is the catalytic converter, a transfer technology from the automobile. The catalytic converter is a noble metal catalyst, such as palladium, coated on ceramic honeycomb substrates and placed directly in the exhaust gas flow, where it reduces the ignition temperature (flash point) of the unburnt hydrocarbons and carbon monoxide. Retrofit catalysts tend to be installed in the flue pipe farther downstream of the woodstove firebox than built-in catalysts. Thus, adequate catalyst operating temperatures may not be achieved with the add on type, resulting in potential flue gas blockage and fire hazards. Limited testing of built-in designs indicates that carbon monoxide and total hydrocarbon emissions are reduced considerably, and efficiency is improved, by the catalyst effect. Some initial findings also indicate that emissions of nitrogen oxides may be increased by as much as a factor of three. Additionally, there is concern that combustion temperatures achieved in stoves operating at representative burn rates (approximately 3 kilograms per hour or less) are not adequate to "light off" the catalyst. Thus, the catalytic unit might reduce emissions but not under all burning conditions.

Emission factors and corresponding emission factor ratings for wood combustion in residential wood stoves are presented in Table 1.10-1.

TABLE 1.10-1. EMISSION FACTORS FOR RESIDENTIAL WOOD STOVES

Pollutant	Wood[a]		Emission Factor Ratings
	g/kg	lb/ton	
Particulate[b,c]	21	42	C
Sulfur oxides[d]	0.2	0.4	A
Nitrogen oxides[e]	1.4	2.8	C
Carbon monoxide[f,c]	130	260	C
VOC[g,c]			
Methane	0.5	1.0	D
Nonmethane	51	100	D

[a] Based on tests burning primarily oak, fir or pine, with moisture content ranging from 15 - 35%.

[b] References 3-6, 8-10, 13-14, 17, 22, 24-25. Includes condensible organics (back half catch of EPA Method 5 or similar test method), which alone account for 54 - 76% of the total mass collected by both front and back half catches (Reference 4). POM is carried by suspended particulate matter and has been found to range from 0.19 - 0.37 g/kg (References 4, 14-15, 22-23) which may include BaP of up to 1.4 mg/kg (Reference 15).

[c] Emissions were determined at burn rates of 3 kg/hr or less. If >3 kg/hr, emissions may decrease by as much as 55 - 60% for particulates and VOC, and 25% for carbon monoxide.

[d] References 2, 4.

[e] Expressed as NO_2. References 3-4, 15, 17, 22-23.

[f] References 3-4, 10-11, 13, 15, 17, 22-23.

[g] References 3-4, 11, 15, 17, 22-23.

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2.4 OPEN BURNING

2.4.1 General[1]

Open burning can be done in open drums or baskets, in fields and yards, and in large open dumps or pits. Materials commonly disposed of in this manner are municipal waste, auto body components, landscape refuse, agricultural field refuse, wood refuse, bulky industrial refuse, and leaves.

2.4.2 Emissions[1-19]

Ground-level open burning is affected by many variables including wind, ambient temperature, composition and moisture content of the debris burned, and compactness of the pile. In general, the relatively low temperatures associated with open burning increase the emission of particulates, carbon monoxide, and hydrocarbons and suppress the emission of nitrogen oxides. Sulfur oxide emissions are a direct function of the sulfur content of the refuse. Emission factors are presented in Table 2.4-1 for the open burning of municipal refuse and automobile components.

Table 2.4-1. EMISSION FACTORS FOR OPEN BURNING OF NONAGRICULTURAL MATERIAL
EMISSION FACTOR RATING: B

Source	Particulate	Sulfur oxides	Carbon monoxide	VOC[a]		Nitrogen oxides
				methane	nonmethane	
Municipal refuse[b]						
kg/Mg	8	0.5	42	6.5	15	3
lb/ton	16	1	85	13	30	6
Automobile components[c]						
kg/Mg	50	Neg.	62	5	16	2
lb/ton	100	Neg.	125	10	32	4

[a] Data indicate that VOC emissions are approximately 25% methane, 8% other saturates, 18% olefins, 42% others (oxygenates, acetylene, aromatics, trace formaldehyde).
[b] References 2, 7.
[c] References 2. Upholstery, belts, hoses and tires burned together.

Emissions from agricultural refuse burning are dependent mainly on the moisture content of the refuse and, in the case of the field crops, on whether the refuse is burned in a headfire or a backfire. (Headfires are started at the upwind side of a field and allowed to progress in the direction of the wind, whereas backfires are started at the downwind edge and forced to progress in a direction opposing the wind.) Other variables such as fuel loading (how much refuse material is burned per unit of land area) and how the refuse is arranged (that is, in piles, rows, or spread out) are also important in certain instances. Emission factors for open agricultural burning are presented in Table 2.4-2 as a function of refuse type and also, in certain instances, as a function of burning techniques and/or moisture content when these variables are known to significantly affect emissions. Table 2.4-2 also presents typical fuel loading values associated with each type of refuse. These values can be used, along with the corresponding emission factors, to estimate emissions from certain categories of agricultural burning when the specific fuel loadings for a given area are not known.

Emissions from leaf burning are dependent upon the moisture content, density, and ignition location of the leaf piles. Increasing the moisture content of the leaves generally increases the amount of carbon monoxide,

Table 2.4-2. EMISSION FACTORS AND FUEL LOADING FACTORS FOR OPEN BURNING OF AGRICULTURAL MATERIALS[a]

EMISSION FACTOR RATING: B

Refuse Category	Particulate[b]		Carbon Monoxide		VOC[c] Methane		VOC[c] Nonmethane		Fuel Loading Factors (waste production)	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	Mg/hectare	ton/acre
Field Crops[d]										
Unspecified	11	21	58	117	2.7	5.4	9	18	4.5	2
Burning techniques not significant[e]										
Asparagus[f]	20	40	75	150	10	20	33	66	3.4	1.5
Barley	11	22	78	157	2.2	4.5	7.5	15	3.8	1.7
Corn	7	14	54	108	2	4	6	12	9.4	4.2
Cotton	4	8	88	176	0.7	1.4	2.5	5	3.8	1.7
Grasses	8	16	50	101	2.2	4.5	7.5	15		
Pineapple[g]	4	8	56	112	1	2	3	6		
Rice[h]	4	9	41	83	1.2	2.4	4	8	6.7	3.0
Safflower	9	18	72	144	3	6	10	20	2.9	1.3
Sorghum	9	18	38	77	1	2	3.5	7	6.5	2.9
Sugar cane[i]	2.5-3.5	6-8.4	30-41	60-81	0.6-2	1.2-3.8	2-6	4-12	8-46	3-17
Headfire burning[j]										
Alfalfa	23	45	53	106	4.2	8.5	14	28	1.8	0.8
Bean (red)	22	43	93	186	5.5	11	18	36	5.6	2.5
Hay (wild)	16	32	70	139	2.5	5	8.5	17	2.2	1.0
Oats	22	44	68	137	4	7.8	13	26	3.6	1.6
Pea	16	31	74	147	4.5	9	15	29	5.6	2.5
Wheat	11	22	64	128	2	4	6.5	13	4.3	1.9
Backfire burning[k]										
Alfalfa	14	29	60	119	4.5	9	14	29	1.8	0.8
Bean (red), pea	7	14	72	148	3	6	10	19	5.6	2.5
Hay (wild)	8	17	75	150	2	4	6.5	13	2.2	1.0
Oats	11	21	68	136	2	4	7	14	3.6	1.6
Wheat	6	13	54	108	1.3	2.6	4.5	9	4.3	1.9
Vine Crops	3	5	26	51	0.8	1.7	3	5	5.6	2.5
Weeds										
Unspecified	8	15	42	85	1.5	3	4.5	9	7.2	3.2
Russian thistle (tumbleweed)	11	22	154	309	0.2	0.5	0.8	1.5	0.2	0.1
Tules (wild reeds)	3	5	17	34	3.2	6.5	10	21		

Orchard Crops[d,l,m]										
Unspecified	3	6	26	52	1.2	2.5	4	8	3.6	1.6
Almond	3	6	23	46	1	2	3	6	3.6	1.6
Apple	2	4	21	42	0.5	1	1.5	3	5.2	2.3
Apricot	3	6	24	49	1	2	3	6	4	1.8
Avocado	10	21	58	116	3.8	7.5	12	25	3.4	1.5
Cherry	4	8	22	44	1.2	2.5	4	8	2.2	1.0
Citrus (orange, lemon)	3	6	40	81	1.5	3	5	9	2.2	1.0
Date palm	5	10	28	56	0.8	1.7	3	5	2.2	1.0
Fig	4	7	28	57	1.2	2.5	4	8	4.9	2.2
Nectarine	2	4	16	33	0.5	1	1.5	3	4.5	2.0
Olive	6	12	57	114	2	4	7	14	2.7	1.2
Peach	3	6	21	42	0.6	1.2	2	4	5.6	2.5
Pear	4	9	28	57	1	2	3.5	7	5.8	2.6
Prune	2	3	21	42	0.4	0.7	1	2	2.7	1.2
Walnut	3	6	24	47	1	2	3	6	2.7	1.2
Forest Residues[n]										
Unspecified	8	17	70	140	2.8	5.7	9	19	157	70
Hemlock, Douglas fir, cedar[p]	2	4	45	90	0.6	1.2	2	4		
Ponderosa pine[q]	6	12	98	195	1.7	3.3	5.5	11		

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[a] Expressed as weight of pollutant emitted/weight of refuse material burned.

[b] Reference 12. Particulate matter from most agricultural refuse burning has been found to be in the submicrometer size range.

[c] Data indicate that VOC emissions average 22% methane, 7.5% other saturates, 17% olefins, 15% acetylene, 38.5% unidentified. Unidentified VOC are expected to include aldehydes, ketones, aromatics, cycloparaffins.

[d] References 12-13 for emission factors, Reference 14 for fuel loading factors.

[e] For these refuse materials, no significant difference exists between emissions from headfiring or backfiring.

[f] Factors represent emissions under typical high moisture conditions. If ferns are dried to <15% moisture, particulate emissions will be reduced by 30%, CO emissions 23%, VOC 74%.

[g] Reference 11. When pineapple is allowed to dry to <20% moisture, as it usually is, firing technique is not important. When headfired at 20% moisture, particulate emissions will increase to 11.5 kg/Mg (23 lb/ton) and VOC will increase to 6.5 kg/Mg (13 lb/ton).

[h] Factors are for dry (15% moisture) rice straw. If rice straw is burned at higher moisture levels, particulate emissions will increase to 14.5 kg/Mg (29 lb/ton), CO emissions to 80.5 kg/Mg (181 lb/ton), and VOC emissions to 11.5 kg/Mg (23 lb/ton).

[i] Reference 20. See Section 8.12 for discussion of sugar cane burning. The following fuel loading factors are to be used in the corresponding states: Louisiana, 8 - 13.6 Mg/hectare (3 - 5 ton/acre); Florida, 11 - 19 Mg/hectare (4 - 7 ton/acre); Hawaii, 30 - 48 Mg/hectare (11 - 17 ton/acre). For other areas, values generally increase with length of growing season. Use the larger end of the emission factor range for lower loading factors.

[j] See text for definition of headfiring.

[k] See text for definition of backfiring. This category, for emission estimation purposes, includes another technique used occasionally to limit emissions, called into-the-wind striplighting, which is lighting fields in strips into the wind at 100 - 200 m (300 - 600 ft) intervals.

[l] Orchard prunings are usually burned in piles. There are no significant differences in emissions between burning a "cold pile" and using a roll-on technique, where prunings are bulldozed onto the embers of a preceding fire.

[m] If orchard removal is the purpose of a burn, 66 Mg/hectare (30 ton/acre) of waste will be produced.

[n] Reference 10. NO_x emissions estimated at 2 kg/Mg (4 lb/ton).

[p] Reference 15.

[q] Reference 16.

hydrocarbon, and particulate emissions. Increasing the density of the piles increases the amount of hydrocarbon and particulate emissions, but has a variable effect on carbon monoxide emissions. Arranging the leaves in conical piles and igniting around the periphery of the bottom proves to the least desirable method of burning. Igniting a single spot on the top of the pile decreases the hydrocarbon and particulate emissions. Carbon monoxide emissions with top ignition decreases if moisture content is high but increases if moisture content is low. Particulate, hydrocarbon, and carbon monoxide emissions from windrow ignition (piling the leaves into a long row and igniting one end, allowing it to burn toward the other end) are intermediate between top and bottom ignition. Emission factors for leaf burning are presented in Table 2.4-3.

For more detailed information on this subject, the reader should consult the references cited at the end of this section.

Table 2.4-3. EMISSION FACTORS FOR LEAF BURNING[18,19]
EMISSION FACTOR RATING: B

Leaf Species	Particulate[b]		Carbon monoxide		VOC[c]			
					Methane		Nonmethane	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Black Ash	18	36	63.5	127	5.5	11	13.5	27
Modesto Ash	16	32	81.5	163	5	10	12	24
White Ash	21.5	43	57	113	6.5	13	16	32
Catalpa	8.5	17	44.5	89	2.5	5	6.5	13
Horse Chestnut	27	54	73.5	147	8	17	20	40
Cottonwood	19	38	45	90	6	12	14	28
American Elm	13	26	59.5	119	4	8	9.5	19
Eucalyptus	18	36	45	90	5.5	11	13.5	27
Sweet Gum	16.5	33	70	140	5	10	12.5	25
Black Locust	35	70	65	130	11	22	26	52
Magnolia	6.5	13	27.5	55	2	4	5	10
Silver Maple	33	66	51	102	10	20	24.5	49
American Sycamore	7.5	15	57.5	115	2.5	5	5.5	11
California Sycamore	5	10	52	104	1.5	3	3.5	7
Tulip	10	20	38.5	77	3	6	7.5	15
Red Oak	46	92	68.5	137	14	28	34	69
Sugar Maple	26.5	53	54	108	8	16	20	40
Unspecified	19	38	56	112	6	12	14	28

[a] References 18-19. Factors are an arithmetic average of results obtained by burning high and low moisture content conical piles, ignited either at the top or around the periphery of the bottom. The windrow arrangement was only tested on Modesto Ash, Catalpa, American Elm, Sweet Gum, Silver Maple and Tulip, and results are included in the averages for these species.

[b] The majority of particulate is submicron in size.

[c] Tests indicate that VOC emissions average 29% methane, 11% other saturates, 33% olefins, 27% other (aromatics, acetylene, oxygenates).

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4.2.2.11 LARGE APPLIANCE SURFACE COATING

General[1] - Large appliance surface coating is the application of protective or decorative organic coatings to preformed large appliance parts. For this discussion, large appliances are defined as any metal range, oven, microwave oven, refrigerator, freezer, washing machine, dryer, dishwasher, water heater or trash compactor.

Regardless of the appliance, similar manufacturing operations are involved. Coiled or sheet metal is cut and stamped into the proper shapes, and the major parts welded together. The welded parts are cleaned with organic degreasers or a caustic detergent (or both) to remove grease and mill scale accumulated during handling, and the parts are then rinsed in one or more water rinses. This is often followed by a process to improve the grain of the metal before treatment in a phosphate bath. Iron or zinc phosphate is commonly used to deposit a microscopic matrix of crystalline phosphate on the surface of the metal. This process provides corrosion resistance and increases the surface area of the part, thereby allowing superior coating adhesion. Often the highly reactive metal is protected with a rust inhibitor to prevent rusting prior to painting.

Two separate coatings have traditionally been applied to these prepared appliance parts, a protective prime coating that also covers surface imperfections and contributes to total coating thickness, and a final, decorative top coat. Single coat systems, where only a prime coat or only a top coat is applied, are becoming more common. For parts not exposed to customer view, a prime coat alone may suffice. For exposed parts, a protective coating may be formulated and applied so as to act as the top coat. There are many different application techniques in the large appliance industry, including manual, automatic and electrostatic spray operations, and several dipping methods. Selection of a particular method depends largely upon the geometry and use of the part, the production rate, and the type of coating being used. Typical application of these coating methods is shown in Figure 4.2.2.11-1.

A wide variety of coating formulations is used by the large appliance industry. The prevalent coating types include epoxies, epoxy/acrylics, acrylics and polyester enamels. Liquid coatings may use either an organic solvent or water as the main carrier for the paint solids.

Waterborne coatings are of three major classes, water solutions, water emulsions and water dispersions. All of the waterborne coatings, however, contain a small amount (up to 20 volume percent) of organic solvent that acts as a stabilizing, dispersing or emulsifying agent. Waterborne systems offer some advantages over organic solvent systems. They do not exhibit as great an increase in viscosity with increasing molecular weight of solids, they are nonflammable, and they have limited toxicity. But because of the relatively slow evaporation rate of water, it is difficult to achieve a smooth finish with waterborne coatings. A bumpy "orange peel" surface often results. For this reason, their main use in the large appliance industry is as prime coats.

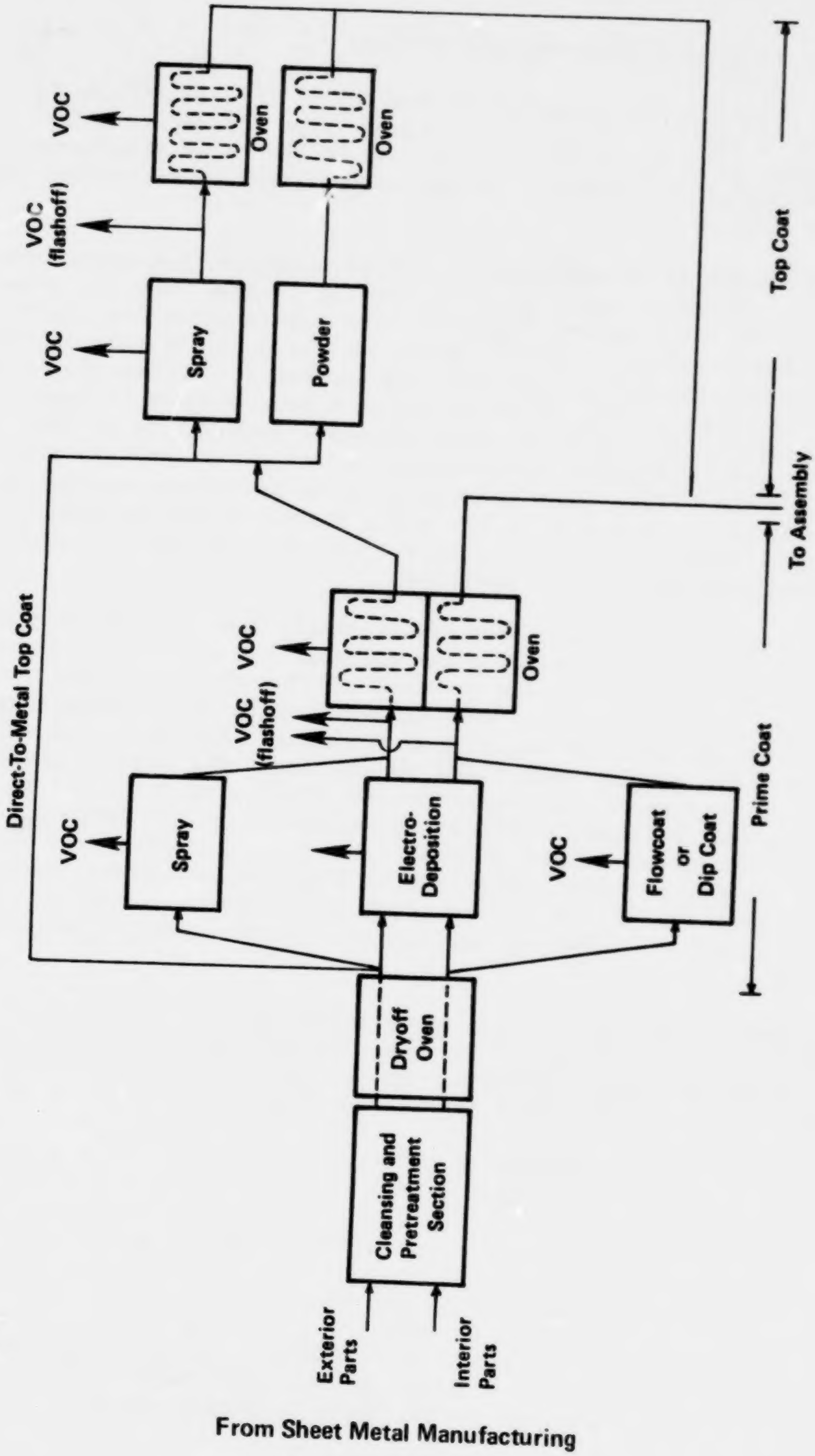

Figure 4.2.2.11-1. Typical coating application methods in the large appliance industry.

While conventional organic solventborne coatings also are used for prime coats, they predominate as top coats. This is due in large part to the controllability of the finish and the amenability of these materials to application by electrostatic spray techniques. The most common organic solvents are ketones, esters, ethers, aromatics and alcohols. To obtain or maintain certain application characteristics, solvents are often added to coatings at the plant. The use of powder coatings for top coats is gaining acceptance in the industry. These coatings, which are applied as a dry powder and then fused into a continuous coating film through the use of heat, yield negligible emissions.

Emissions and Controls[1-2] - Volatile organic compounds (VOC) are the major pollutants emitted from large appliance surface coating operations. VOC from evaporation of organic solvents contained in the coating are emitted in the application station, the flashoff area and the oven. An estimated 80 percent of total VOC emissions is given off in the application station and flashoff area. The remaining 20 percent occurs in the oven. Because the emissions are widely dispersed, the use of capture systems and control devices is not an economically attractive means of controlling emissions. While both incinerators and carbon adsorbers are technically feasible, none is known to be used in production, and none is expected. Improvements in coating formulation and application efficiency are the major means of reducing emissions.

Factors that affect the emission rate include the volume of coating used, the coating's solids content, the coating's VOC content, and the VOC density. The volume of coating used is a function of three additional variables, 1) the area coated, 2) the coating thickness and 3) the application efficiency.

While a reduction in coating VOC content will reduce emissions, the transfer efficiency with which the coating is applied (i.e., the volume required to coat a given surface area) also has a direct bearing on the emissions. A transfer efficiency of 60 percent means that 60 percent of the coating solids consumed is deposited usefully onto appliance parts. The other 40 percent is wasted overspray. With a specified VOC content, an application system with a high transfer efficiency will have lower emission levels than will a system with a low transfer efficiency, because a smaller volume of coating will coat the same surface area. Since not every application method can be used with all parts and types of coating, transfer efficiencies in this industry range from 40 to over 95 percent.

Although waterborne prime coats are becoming common, the trend for top coats appears to be toward use of "high solids" solventborne material, generally 60 volume percent or greater solids. As different types of coatings are required to meet different performance specifications, a combination of reduced coating VOC content and improved transfer efficiency is the most common means of emission reduction.

In the absence of control systems that remove or destroy a known fraction of the VOC prior to emission to the atmosphere, a material balance provides the quickest and most accurate emissions estimate. An equation to calculate emissions is presented below. To the extent that the parameters of this equation are known or can be determined, its use is encouraged. In the event that both a prime coat and a top coat are used, the emissions from each must be calculated separately and added to estimate total emissions. Because of the diversity of product mix and plant sizes, it is difficult to provide emission factors for "typical" facilities. Approximate values for several of the variables in the equation are provided, however.

$$E = \frac{(6.234 \times 10^{-4})\ P\ A\ t\ V_o\ D_o}{V_s T} + L_d\ D_d$$

where

E = mass of VOC emissions per unit time (lb/unit time)
P = units of production per unit time
A = area coated per unit of production (ft^2)
t = dry coating thickness (mils)
V_o = proportion of VOC in the coating (volume fraction), as received*
D_o = density of VOC solvent in the coating (lb/gal), as received*
V_s = proportion of solids in the coating (volume fraction), as received*
T = transfer efficiency (fraction - the ratio of coating solids deposited onto appliance parts to the total amount of coating solids used. See Table 4.2.2.11-1).
L_d = volume of VOC solvent added to the coating per unit time (gal/unit time).
D_d = density of VOC solvent added (lb/gal).

The constant 6.234×10^{-4} is the product of two conversion factors:

$$\frac{8.333 \times 10^{-5}\ \text{ft}}{\text{mil}} \text{ and } \frac{7.481\ \text{gal}}{\text{ft}^3}.$$

If all the data are not available to complete the above equation, the following may be used as approximations:

V_o = 0.38
D_o = 7.36 lb/gal
V_s = 0.62
L_d = 0 (assumes no solvent added at the plant).

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*If known, V_o, D_o and V_s for the coating as applied (i.e., diluted) may be used in lieu of the values for the coating as received, and the term $L_d D_d$ deleted.

TABLE 4.2.2.11-1. TRANSFER EFFICIENCIES

Application Method	Transfer Efficiency (T)
Air atomized spray	0.40
Airless spray	0.45
Manual electrostatic spray	0.60
Flow coat	0.85
Dip coat	0.85
Nonrotational automatic electrostatic spray	0.85
Rotating head automatic electrostatic spray	0.90
Electrodeposition	0.95
Powder	0.95

TABLE 4.2.2.11-2. AREAS COATED AND COATING THICKNESS

	Prime Coat		Top Coat	
Appliance	A(ft^2)	t(mils)	A(ft^2)	t(mils)
Compactor	20	0.5	20	0.8
Dishwasher	10	0.5	10	0.8
Dryer	90	0.6	30	1.2
Freezer	75	0.5	75	0.8
Microwave oven	8	0.5	8	0.8
Range	20	0.5	30	0.8
Refrigerator	75	0.5	75	0.8
Washing machine	70	0.6	25	1.2
Water heater	20	0.5	20	0.8

In the absence of all operating data, an emission estimate of 49.9 Mg (55 tons) of VOC per year may be used for the average appliance plant. Because of the large variation in emissions among plants (from less than 10 to more than 225 Mg [10 to 250 tons] per year), caution is advised when this estimate is used for anything except approximations for a large geographical area. Most of the known large appliance plants are in localities considered nonattainment areas for achieving the national ambient air quality standard (NAAQS) for ozone. The 49.9-Mg-per-year average is based on an emission limit of 2.8 lb/VOC per gallon of coating (minus water), which is the limit recommended by the Control Techniques Guideline (CTG) applicable in those areas. For a plant operating in an area where there are no emission limits, the emissions may be four times greater than from an identical plant subject to the CTG recommended limit.

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4.2.2.12 METAL FURNITURE SURFACE COATING

4.2.2.12.1 General

The metal furniture surface coating process is a multistep operation consisting of surface cleaning and coatings application and curing. Items such as desks, chairs, tables, cabinets, bookcases and lockers are normally fabricated from raw material to finished product in the same facility. The industry uses primarily solventborne coatings, applied by spray, dip or flow coating processes. Spray coating is the most common application technique used. The components of spray coating lines vary from plant to plant but generally consist of the following:

Three to five stage washer
Dryoff oven
Spray booth
Flashoff area
Bake oven

Items to be coated are first cleaned in the washer to remove any grease, oil or dirt from the surface. The washer generally consists of an alkaline cleaning solution, a phosphate treatment to improve surface adhesion characteristics, and a hot water rinse. The items are then dried in an oven and conveyed to the spray booth, where the surface coating is applied. After this application, the items are conveyed through the flashoff area to the bake oven, where the surface coating is cured. A diagram of these consecutive steps is presented in Figure 4.2.2.12-1. Although most metal furniture products receive only one coat of paint, some facilities apply a prime coat before the top coating to improve the corrosion resistance of the product. In these cases, a separate spray booth and bake oven for application of the prime coat are added to the line, following the dryoff oven.

The coatings used in the industry are primarily solventborne resins, including acrylics, amines, vinyls and cellulosics. Some metallic coatings are also used on office furniture. The solvents used are mixtures of aliphatics, xylene, toluene and other aromatics. Typical coatings that have been used in the industry contain 65 volume percent solvent and 35 volume percent solids. Other types of coatings now being used in the industry are waterborne, powder and solventborne high solids coatings.

4.2.2.12.2 Emissions and Controls

Volatile organic compounds (VOC) from the evaporation of organic solvents in the coatings are the major pollutants from metal furniture surface coating operations. Specific operations that emit VOC are the coating application process, the flashoff area and the bake oven. The percentage of total VOC emissions given off at each emission point varies from one installation to another, but on the average spray coating line, about 40 percent is given off at the application station, 30 percent in the flashoff area, and 30 percent in the bake oven.

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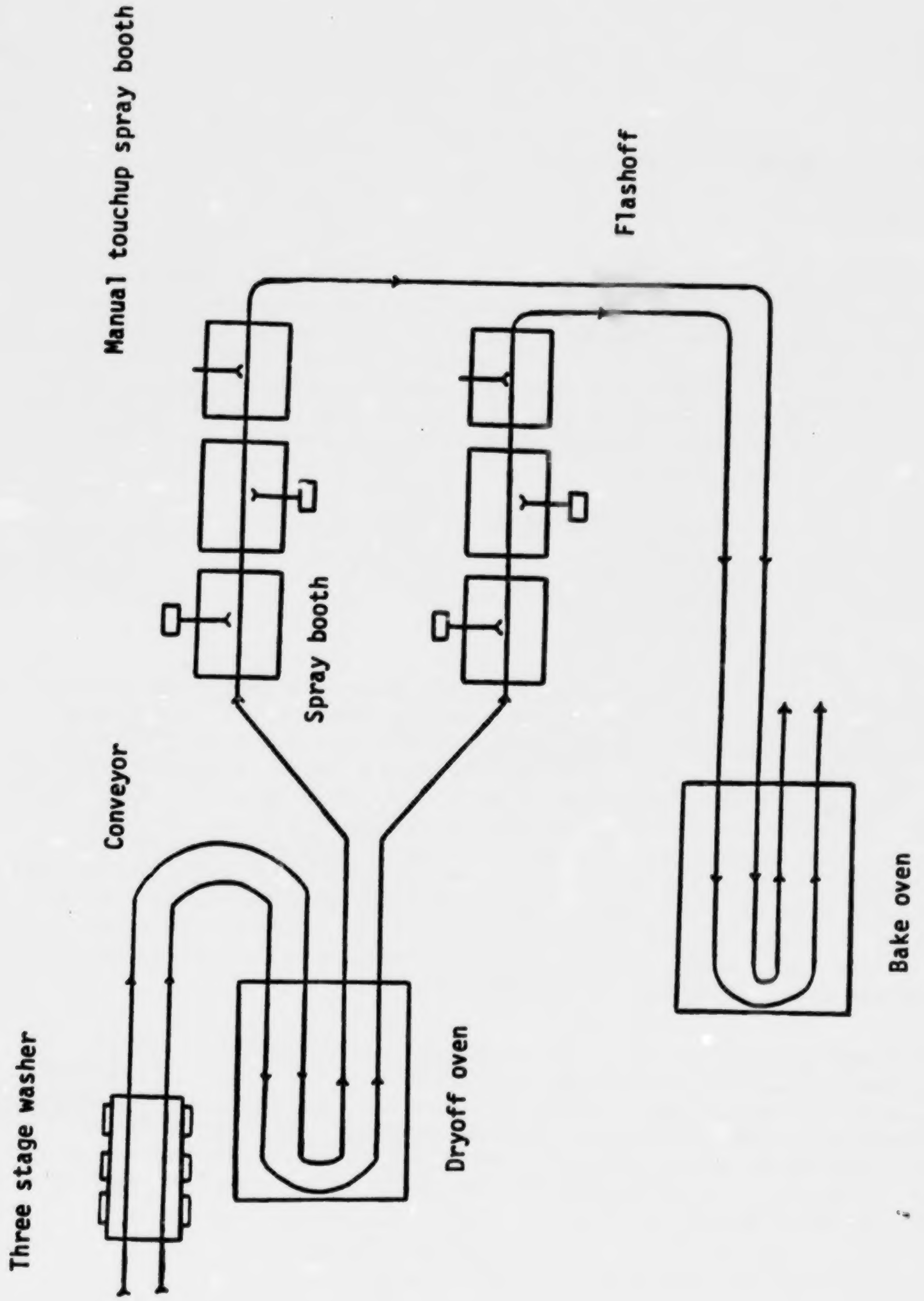


Figure 4.2.2.12-1. Example automated spray coating lines, with manual touchup.

Factors affecting the quantity of VOC emitted from metal furniture surface coating operations are the VOC content of the coatings applied, the solids content of coatings as applied and the transfer efficiency. Knowledge of both the VOC content and solids content of coatings is necessary in cases where the coating contains other components, such as water.

The transfer efficiency (volume fraction of the solids in the total consumed coating that remains on the part) varies with the application technique. Transfer efficiency for standard (or ordinary) spraying ranges from 25 to 50 percent. The range for electrostatic spraying, a method that uses an electrical potential to increase transfer efficiency of the coating solids, is from 50 to 95 percent, depending on part size and shape. Powder coating systems normally capture and recirculate overspray material and, therefore, are considered in terms of a "utilization rate" rather than a transfer efficiency. Most facilities achieve a powder utilization rate of 90 to 95 percent.

Typical values for transfer efficiency with various application devices are in Table 4.2.2.12-1.

Two types of control techniques are available to reduce VOC emissions from metal furniture surface coating operations. The first technique makes use of control devices such as carbon adsorbers and thermal or catalytic incinerators to recover or destroy VOC before it is discharged into the ambient air. These control methods are seldom used in the industry, however, because the large volume of exhaust air and low concentrations of VOC in the exhaust reduce their efficiency. The more prevalent control technique involves reducing the total amount of VOC likely to be evaporated and emitted. This is accomplished by use of low VOC content coatings and by improvements in transfer efficiency. New coatings with relatively low VOC levels can be used instead of the traditional high VOC content coatings. Examples of these new systems include waterborne coatings, powder coatings, and higher solids coatings. Improvements in coating transfer efficiency decrease the amount that must be used to achieve a given film thickness, thereby reducing emissions of VOC to the ambient air. By using a system with increased transfer efficiency (such as electrostatic spraying) and lower VOC content coatings, VOC emission reductions can approach those achieved with control devices.

The data presented in Tables 4.2.2.12-2 and 4.2.2.12-3 are representative of values which might be obtained from existing plants with similar operating characteristics. Each plant has its own combination of coating formulations, application equipment and operating parameters. It is recommended that, whenever possible, plant specific values be obtained for all variables when calculating emission estimates.

Another method that also may be used to estimate emissions for metal furniture coating operations involves a material balance approach. By assuming that all VOC in the coatings applied are evaporated at the plant site, an estimate of emissions can be calculated using only the coating formulation and data on the total quantity of coatings used in a given time period. The percentage of VOC solvent in the coating, multiplied by the quantity of coatings used yields the total emissions. This method of emissions estimation avoids the requirement to use variables such as coating thickness and transfer efficiency, which are often difficult to define precisely.

TABLE 4.2.2.12-1. COATING METHOD TRANSFER EFFICIENCIES

Application Methods	Transfer Efficiency (Te)
Air atomized spray	0.25
Airless spray	0.25
Manual electrostatic spray	0.60
Nonrotational automatic electrostatic spray	0.70
Rotating head electrostatic spray (manual and automatic)	0.80
Dip coat and flow coat	0.90
Electrodeposition	0.95

TABLE 4.2.2.12-2. OPERATING PARAMETERS FOR COATING OPERATIONS

Plant size	Operating schedule (hr/yr)	Number of lines	Line speed[a] (m/min)	Surface area coated/yr (m^2)	Liters of coating used[b]
Small	2,000	1 (1 spray booth)	2.5	45,000	5,000
Medium	2,000	2 (3 booths/line)	2.4	780,000	87,100
Large	2,000	10 (3 booths/line)	4.6	4,000,000	446,600

[a] Line speed is not used to calculate emissions, only to characterize plant operations.

[b] Using 35 volume % solids coating, applied by electrostatic spray at 65 % transfer efficiency.

TABLE 4.2.2.12-3. EMISSION FACTORS FOR VOC FROM SURFACE COATING OPERATIONS[a,b]

Plant Size and Control Techniques	VOC Emissions		
	kg/m^2 coated	kg/year	kg/hour
Small			
Uncontrolled emissions	.064	2,875	1.44
65 volume % high solids coating	.019	835	.42
Waterborne coating	.012	520	.26
Medium			
Uncontrolled emissions	.064	49,815	24.90
65 volume % high solids coating	.019	14,445	7.22
Waterborne coating	.012	8,970	4.48
Large			
Uncontrolled emissions	.064	255,450	127.74
65 volume % high solids coating	.019	74,080	37.04
Waterborne coating	.012	46,000	23.00

[a] Calculated using the parameters given in Table 4.2.2.12-2 and the following equation. Values have been rounded off.

$$E = \frac{0.0254\ A\ T\ V\ D}{S\ Te}$$

where E = Mass of VOC emitted per hour (kg)
A = Surface area coated per hour (m^2)
T = Dry film thickness of coating applied (mils)
V = VOC content of coating; including dilution solvents added at the plant (fraction by volume)
D = VOC density (assumed to be 0.88 kg/l)
S = Solids content of coating (fraction by volume)
Te = Transfer efficiency (fraction)

The constant 0.0254 converts the volume of dry film applied per m^2 to liters.

Example: The VOC emission from a medium size plant applying 35 volume % solids coatings and the parameters given in Table 4.2.2.12-3.

$$E_{\text{Kilograms of VOC/hr}} = \frac{0.0254(390 m^2/hr)(1\ mil)(0.65)(0.88\ kg/l)}{(0.35)(0.65)}$$

$$= 24.9 \text{ kilograms of VOC per hour}$$

[b] Nominal values of T, V, S and Te:

T = 1 mil (for all cases)
V = 0.65 (uncontrolled), 0.35 (65 volume % solids), 0.117 (waterborne)
S = 0.35 (uncontrolled, 0.65 (65 volume % solids), 0.35 (waterborne)
Te = 0.65 (for all cases)

Reference for Section 4.2.2.12

1. Surface Coating of Metal Furniture - Background Information for Proposed Standards, EPA-450/3-80-007a, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1980.

5.0 CHEMICAL PROCESS INDUSTRY

This Chapter deals with emissions from the manufacture and use of chemicals or chemical products. Potential emissions from many of these processes are high, but because of economic necessity, they are usually recovered. In some cases, the manufacturing operation is run as a closed system, allowing little or no emissions to escape to the atmosphere.

The emissions that reach the atmosphere from chemical processes are generally gaseous and are controlled by incineration, adsorption or absorption. Particulate emissions may also be a problem, since the particulates emitted are usually extremely small, requiring very efficient treatment for removal. Emissions data from chemical processes are sparse. It has been, therefore, frequently necessary to make estimates of emission factors on the basis of material balances, yields or similar processes.

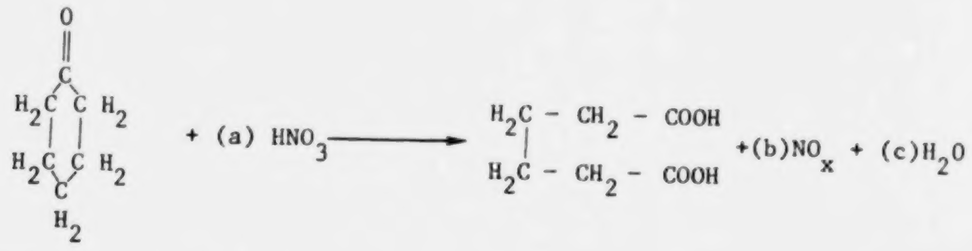
5.1 ADIPIC ACID

5.1.1 General[1-2]

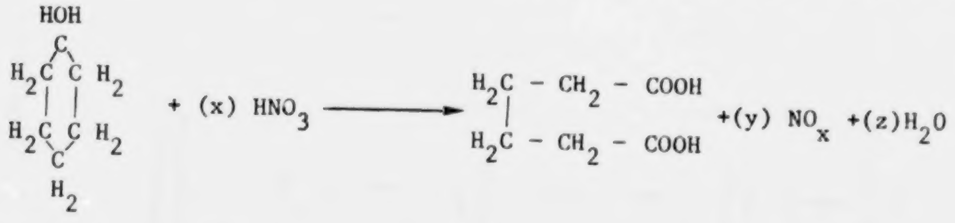
Adipic acid, $HOOC(CH_2)_4COOH$, is a white crystalline solid used in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers and synthetic lubricants. Ninety percent of all adipic acid produced in the United States is used in manufacturing Nylon 6,6. Cyclohexane is the basic raw material generally used to produce adipic acid, however, one plant uses cyclohexanone, a byproduct of another process. Phenol has also been used but has proven to be more expensive and less readily available than cyclohexane.

5.1.2 Process Description[1-4]

During adipic acid production, the raw material, cyclohexane or cyclohexanone, is transferred to a reactor, where it is oxidized at 130 to 170°C (260 - 330°F) to form a cyclohexanol/cyclohexanone mixture. The mixture is then transferred to a second reactor and is oxidized with nitric acid and a catalyst (usually a mixture of cupric nitrate and ammonium metavanadate) at 70 to 100°C (160 - 220°F) to form adipic acid. The chemistry of these reactions is shown below.



Cyclohexanone + Nitric acid ⟶ Adipic acid + Nitrogen oxides + Water



Cyclohexanol + Nitric acid ⟶ Adipic acid + Nitrogen oxides + Water

An alternate route for synthesizing adipic acid from cyclohexane (I. G. Farben process) involves two air oxidation steps: cyclohexane is oxidized to cyclohexanol and cyclohexanone; cyclohexanone and cyclohexanol are then oxidized to adipic acid, with a mixed manganese/barium acetate used as the catalyst.

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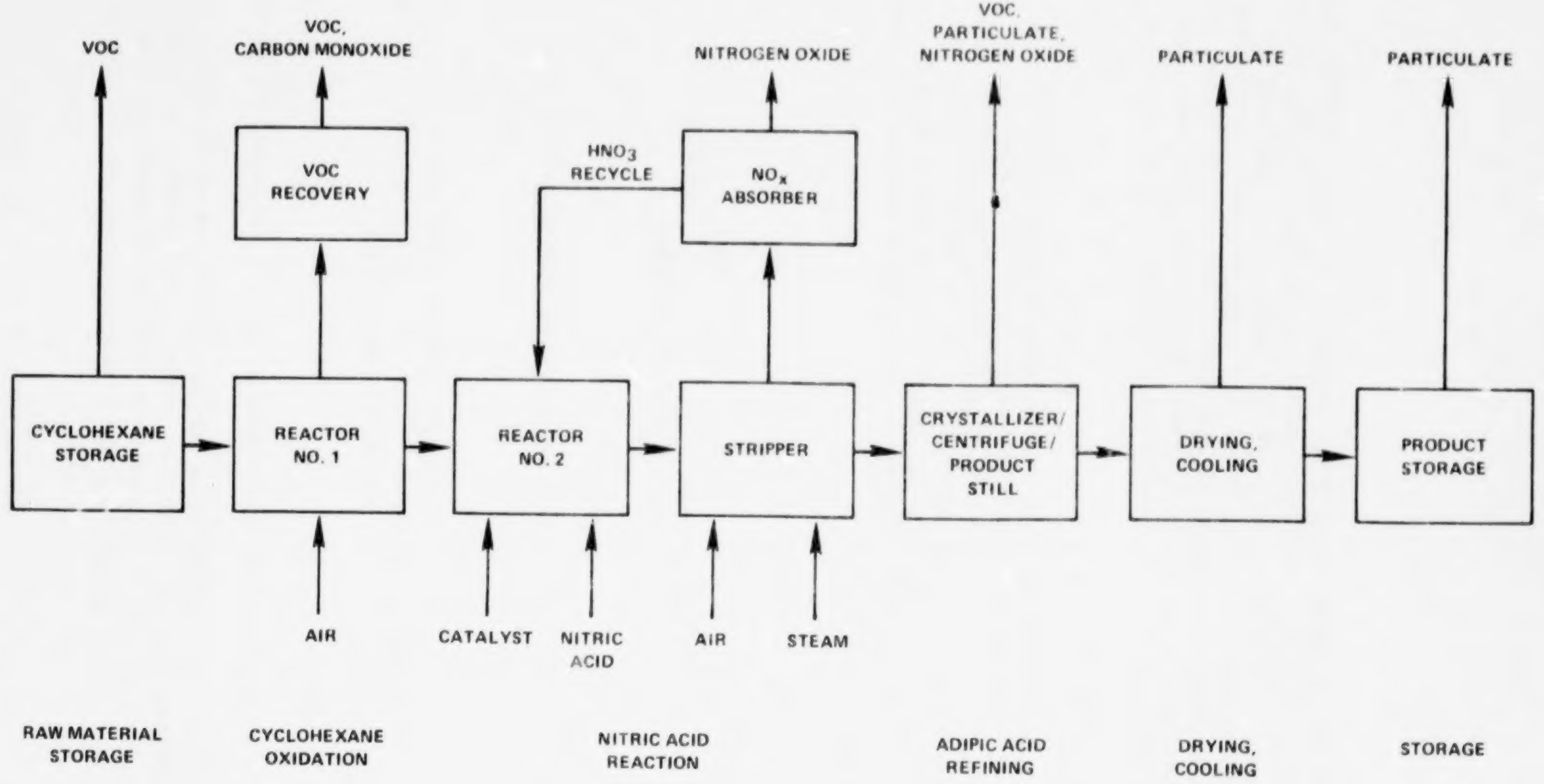

Figure 5.1-1. General Flow diagram of adipic acid manufacturing process.

Another possible synthesis method is a direct one stage air oxidation of cyclohexane to adipic acid with a cobaltous acetate catalyst.

The product from the second reactor enters a bleacher, in which the dissolved nitrogen oxides are stripped from the adipic acid/nitric acid solution with air and steam. Various organic acid byproducts, namely acetic acid, glutaric acid and succinic acid, are also formed and may be recovered and sold by some plants.

The adipic acid/nitric acid solution is chilled and sent to a vacuum crystallizer, where adipic acid crystals are formed, and the solution is then centrifuged to separate the crystals. The remaining solution is sent to another vacuum crystallizer, where any residual adipic acid is crystallized and centrifugally separated. Wet adipic acid from the last crystallization stage is dried and cooled and then is transferred to a storage bin. The remaining solution is distilled to recover nitric acid, which is routed back to the second reactor for reuse. Figure 5.1-1 presents a general scheme of the adipic acid manufacturing process.

5.1.3 Emissions and Controls[1,5]

Nitrogen oxides (NO_x), volatile organic compounds (VOC) and carbon monoxide (CO) are the major pollutants from adipic acid production. The cyclohexane reactor is the largest source of CO and VOC, and the nitric acid reactor is the dominant source of NO_x. Drying and cooling of the adipic acid product create particulate emissions, which are generally low because baghouses and/or wet scrubbers are employed for maximum product recovery and air pollution control. Process pumps and valves are potential sources of fugitive VOC emissions. Secondary emissions occur only from aqueous effluent discharged from the plant by pipeline to a holding pond. Aqueous effluent from the adipic acid manufacturing process contains dibasic organic acids, such as succinic and glutaric. Since these compounds are not volatile, air emissions are negligible compared to other emissions of VOC from the plant. Figure 5.1-1 shows the points of emission of all process pollutants.

The most significant emissions of VOC and CO come from the cyclohexane oxidation unit, which is equipped with high and low pressure scrubbers. Scrubbers have a 90 percent collection efficiency of VOC and are used for economic reasons, to recover expensive volatile organic compounds as well as for pollution control. Thermal incinerators, flaring and carbon adsorbers can all be used to limit VOC emissions from the cyclohexane oxidation unit with a greater than 90 percent efficiency. CO boilers control CO emissions with 99.99 percent efficiency and VOC emissions with practically 100 percent efficiency. The combined use of a CO boiler and a pressure scrubber results in nearly complete VOC and CO control.

Three methods are presently used to control emissions from the NO_x absorber: water scrubbing, thermal reduction, and flaring or combustion in a powerhouse boiler. Water scrubbers have a low collection efficiency, approximately 70 percent, because of the extensive time needed to remove insoluble NO in the absorber offgas stream. Thermal reduction, in which offgases containing NO_x are heated to high temperatures and are reacted with excess fuel in a reducing atmosphere, operates at up to 97.5 percent efficiency and is believed to be the most effective system of control. Burning offgas in a powerhouse or flaring has an estimated efficiency of 70 percent.

TABLE 5.1-1. EMISSION FACTORS FOR ADIPIC ACID MANUFACTURE[a]

EMISSION FACTOR RATING: B

Process	Adipic acid particulate		Nitrogen oxides[b]		Nonmethane volatile organic compounds		Carbon monoxide	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Raw material storage								
Uncontrolled	0	0	0	0	1.1	2.2	0	0
Cyclohexane oxidation								
Uncontrolled[c]	0	0	0	0	20	40	58	115
W/boiler	0	0	0	0	Neg	Neg	0.5	1
W/thermal incinerator[d]	0	0	0	0	Neg	Neg	Neg	Neg
W/flaring[e]	0	0	0	0	2	4	6	12
W/carbon absorber[f]	0	0	0	0	1	2	58	115
W/scrubber plus boiler	0	0	0	0	Neg	Neg	Neg	Neg
Nitric acid reaction								
Uncontrolled[g]	0	0	27	53	0	0	0	0
W/water scrubber[h]	0	0	8	16	0	0	0	0
W/thermal reduction[i]	0	0	0.5	1	0	0	0	0
W/flaring or combustion[h]	0	0	8	16	0	0	0	0
Adipic acid refining[j]								
Uncontrolled	0.1[k]	0.1[k]	0.3	0.6	0.3	0.5	0	0
Adipic acid drying, cooling and storage	0.4[k]	0.8[k]	0	0	0	0	0	0

[a] Reference 1. Factors are in lb of pollutant/ton and kg of pollutant/Mg of adipic acid produced. Neg = Negligible.

[b] NO_x is in the form of NO and NO_2. Although large quantities of N_2O are also produced, N_2O is not a criteria pollutant and is not, therefore, included here.

[c] Factors are after scrubber processing, since hydrocarbon recovery using scrubbers is an integral part of adipic acid manufacturing.

[d] A thermal incinerator is assumed to reduce VOC and CO emissions by approximately 99.99%.

[e] A flaring system is assumed to reduce VOC and CO emissions by 90%.

[f] A carbon adsorber is assumed to reduce VOC emissions by 94% and to be ineffective in reducing CO emissions.

[g] Uncontrolled emission factors are after NO_x absorber, since nitric acid recovery is an integral part of adipic acid manufacturing.

[h] Estimated 70% control.

[i] Estimated 97.5% control.

[j] Includes chilling, crystallization and centrifuging.

[k] Factors are after baghouse control device.

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References for Section 5.1

1. Screening Study To Determine Need for Standards of Performance for New Adipic Acid Plants, EPA Contract No. 68-02-1316, GCA/Technology Division, Bedford, MA, July 1976.

2. Kirk-Othmer Encyclopedia of Chemical Technology, "Adipic Acid", Vol. 1, 2nd Ed, New York, Interscience Encyclopedia, Inc, 1967.

3. M. E. O'Leary, "CEH Marketing Research Report on Adipic Acid", Chemical Economics Handbook, Stanford Research Institute, Menlo Park, CA, January 1974.

4. K. Tanaka, "Adipic Acid by Single Stage", Hydrocarbon Processing, 55(11), November 1974.

5. H. S. Bosdekis, Adipic Acid in Organic Chemical Manufacturing, Volume 6, EPA-450/3-80-028a, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1980.

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5.2 SYNTHETIC AMMONIA

5.2.1 General

Anhydrous ammonia is synthesized by reacting hydrogen with nitrogen at a molar ratio of 3:1, then compressing the gas and cooling it to -33°C. Nitrogen is obtained from the air, while hydrogen is obtained from either the catalytic steam reforming of natural gas (methane) or naphtha, or the electrolysis of brine at chlorine plants. In the United States, about 98 percent of synthetic ammonia is produced by catalytic steam reforming of natural gas (Figure 5.2-1).

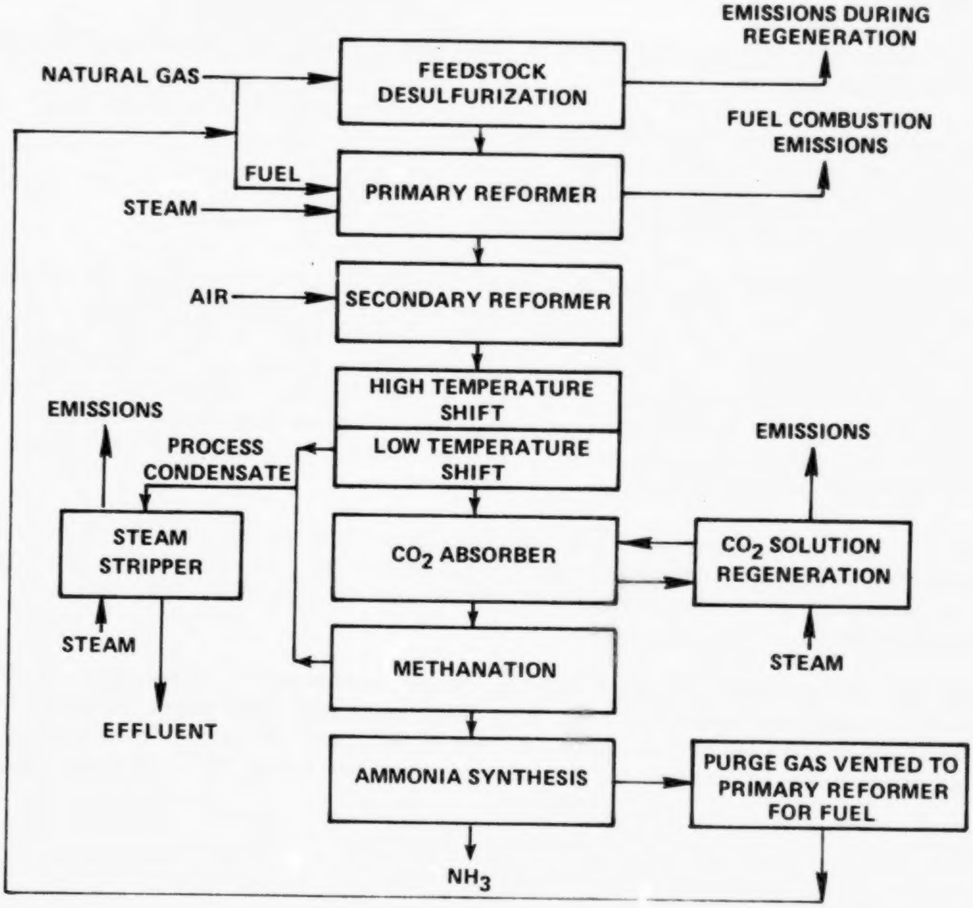

Figure 5.2-1. General process flow diagram of a typical ammonia plant.

Seven process steps are required to produce synthetic ammonia by the catalytic steam reforming method:

Natural gas desulfurization
Primary reforming with steam
Secondary reforming with air
Carbon monoxide shift
Carbon dioxide removal
Methanation
Ammonia synthesis

The first, fourth, fifth and sixth steps are to remove impurities such as sulfur, CO, CO_2 and water from the feedstock, hydrogen and synthesis gas streams. In the second step, hydrogen is manufactured, and in the third step, additional hydrogen is manufactured and nitrogen is introduced into the process. The seventh step produces anhydrous ammonia from the synthetic gas. While all ammonia plants use this basic process, details such as pressures, temperatures and quantities of feedstock will vary from plant to plant.

5.2.2 Emissions

Pollutants from the manufacture of synthetic anhydrous ammonia are emitted from four process steps:

Regeneration of the desulfurization bed
Heating of the primary reformer
Regeneration of carbon dioxide scrubbing solution
Steam stripping of process condensate

More than 95 percent of the ammonia plants in the U. S. use activated carbon fortified with metallic oxide additives for feedstock desulfurization. The desulfurization bed must be regenerated about once every 30 days for a 10-hour period. Vented regeneration steam contains sulfur oxides and/or hydrogen sulfide, depending on the amount of oxygen in the steam. Regeneration also emits volatile organic compounds (VOC) and carbon monoxide. The primary reformer, heated with natural gas or fuel oil, emits the combustion products NO_x, CO, SO_x, VOC and particulates.

Carbon dioxide is removed from the synthesis gas by scrubbing with monoethanolamine or hot potassium carbonate solution. Regeneration of this CO_2 scrubbing solution with steam produces emissions of VOC, NH_3, CO, CO_2 and monoethanolamine.

Cooling the synthesis gas after low temperature shift conversion forms a condensate containing quantities of NH_3, CO_2, methanol and trace metals. Condensate steam strippers are used to remove NH_3 and methanol from the water, and steam from this is vented to the atmosphere, emitting NH_3, CO_2 and methanol.

Table 5.2-1 presents emission factors for the typical ammonia plant. Control devices are not used at such plants, so the values in Table 5.2-1 represent uncontrolled emissions.

5.2.3 Controls

Add-on air pollution control devices are not used at synthetic ammonia plants, because their emissions are below state standards. Some processes have been modified to reduce emissions and to improve utility of raw materials and energy. Some plants are considering techniques to eliminate emissions from the condensate steam stripper, one such being the injection of the overheads into the reformer stack along with the combustion gases.

TABLE 5.2-1. UNCONTROLLED EMISSION FACTORS FOR TYPICAL AMMONIA PLANT[a]

EMISSION FACTOR RATING: A

Emission Point	Pollutant	kg/Mg	lb/ton
Desulfurization unit regeneration[b]	Total sulfur[c,d]	0.0096	0.019
	CO	6.9	13.8
	Nonmethane VOC[e]	3.6	7.2
Primary reformer, heater fuel combustion			
Natural gas	NO_x	2.7	5.4
	SO_x	0.0024	0.0048
	CO	0.068	0.136
	Particulates	0.072	0.144
	Methane	0.0063	0.0125
	Nonmethane VOC	0.0061	0.0122
Distillate oil	NO_x	2.7	5.4
	SO_x	1.3	2.6
	CO	0.12	0.24
	Particulates	0.45	0.90
	Methane	0.03	0.06
	Nonmethane VOC	0.19	0.38
Carbon dioxide regenerator	Ammonia	1.0	2.0
	CO	1.0	2.0
	CO_2	1220	2440
	Nonmethane VOC[f]	0.52	1.04
Condensate steam stripper	Ammonia	1.1	2.2
	CO_2	3.4	6.8
	Nonmethane VOC[g]	0.6	1.2

[a] Emission factors are expressed in weight of emissions per unit weight of ammonia produced.

[b] Intermittent source, average 10 hours once every 30 days.

[c] Worst case assumption, that all sulfur entering tank is emitted during regeneration.

[d] Normalized to a 24 hour emission factor.

[e] Reference 2.

[f] 0.05 kg/MT (0.1 lb/ton) is monoethanolamine.

[g] Mostly methanol.

References for Section 5.2

1. G. D. Rawlings and R. B. Reznik, Source Assessment: Synthetic Ammonia Production, EPA-600/2-77-107m, U. S. Environmental Protection Agency, Research Triangle Park, NC, November 1977.

2. Source Category Survey: Ammonia Manufacturing Industry, EPA-450/3-80-014, U. S. Environmental Protection Agency, Research Triangle Park, NC, August 1980.

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5.3 CARBON BLACK

5.3.1 Process Description

Carbon black is produced by the reaction of a hydrocarbon fuel such as oil or gas with a limited supply of combustion air at temperatures of 1320 to 1540°C (2400 to 2800°F). The unburned carbon is collected as an extremely fine black fluffy particle, 10 to 500 nm diameter. The principal uses of carbon black are as a reinforcing agent in rubber compounds (especially tires) and as a black pigment in printing inks, surface coatings, paper and plastics. Two major processes are presently used in the United States to manufacture carbon black, the oil furnace process and the thermal process. The oil furnace process accounts for about 90 percent of production, and the thermal about 10 percent. Two others, the lamp process for production of lamp black and the cracking of acetylene to produce acetylene black, are each used at one plant in the U. S. However, these are small volume specialty black operations which constitute less than 1 percent of total production in this country. The gas furnace process is being phased out, and the last channel black plant in the U. S. was closed in 1976.

5.3.1.1 Oil Furnace Process - In the oil furnace process (Figure 5.3-1 and Table 5.3-1), an aromatic liquid hydrocarbon feedstock is heated and injected continuously into the combustion zone of a natural gas fired furnace, where it is decomposed to form carbon black. Primary quench water cools the gases to 500°C (1000°F) to stop the cracking. The exhaust gases entraining the carbon particles are further cooled to about 230°C (450°F) by passage through heat exchangers and direct water sprays. The black is then separated from the gas stream, usually by a fabric filter. A cyclone for primary collection and particle agglomeration may precede the filter. A single collection system often serves several manifolded furnaces.

The recovered carbon black is finished to a marketable product by pulverizing and wet pelletizing to increase bulk density. Water from the wet pelletizer is driven off in a gas fired rotary dryer. Oil or process gas can be used. From 35 to 70 percent of the dryer combustion gas is charged directly to the interior of the dryer, and the remainder acts as an indirect heat source for the dryer. The dried pellets are then conveyed to bulk storage. Process yields range from 35 to 65 percent, depending on the feed composition and the grade of black produced. Furnace designs and operating conditions determine the particle size and the other physical and chemical properties of the black. Generally, yields are highest for large particle blacks and lowest for small particle blacks.

5.3.1.2 Thermal Process - The thermal process is a cyclic operation in which natural gas is thermally decomposed (cracked) into carbon particles, hydrogen and a mixture of other organics. Two furnaces are used in normal operation. The first cracks natural gas and makes carbon black and hydrogen. The effluent gas from the first reactor is cooled by water sprays to about 125°C (250°F), and the black is collected in a fabric filter. The filtered gas (90 percent hydrogen, 6 percent methane and 4 percent higher hydrocarbons)

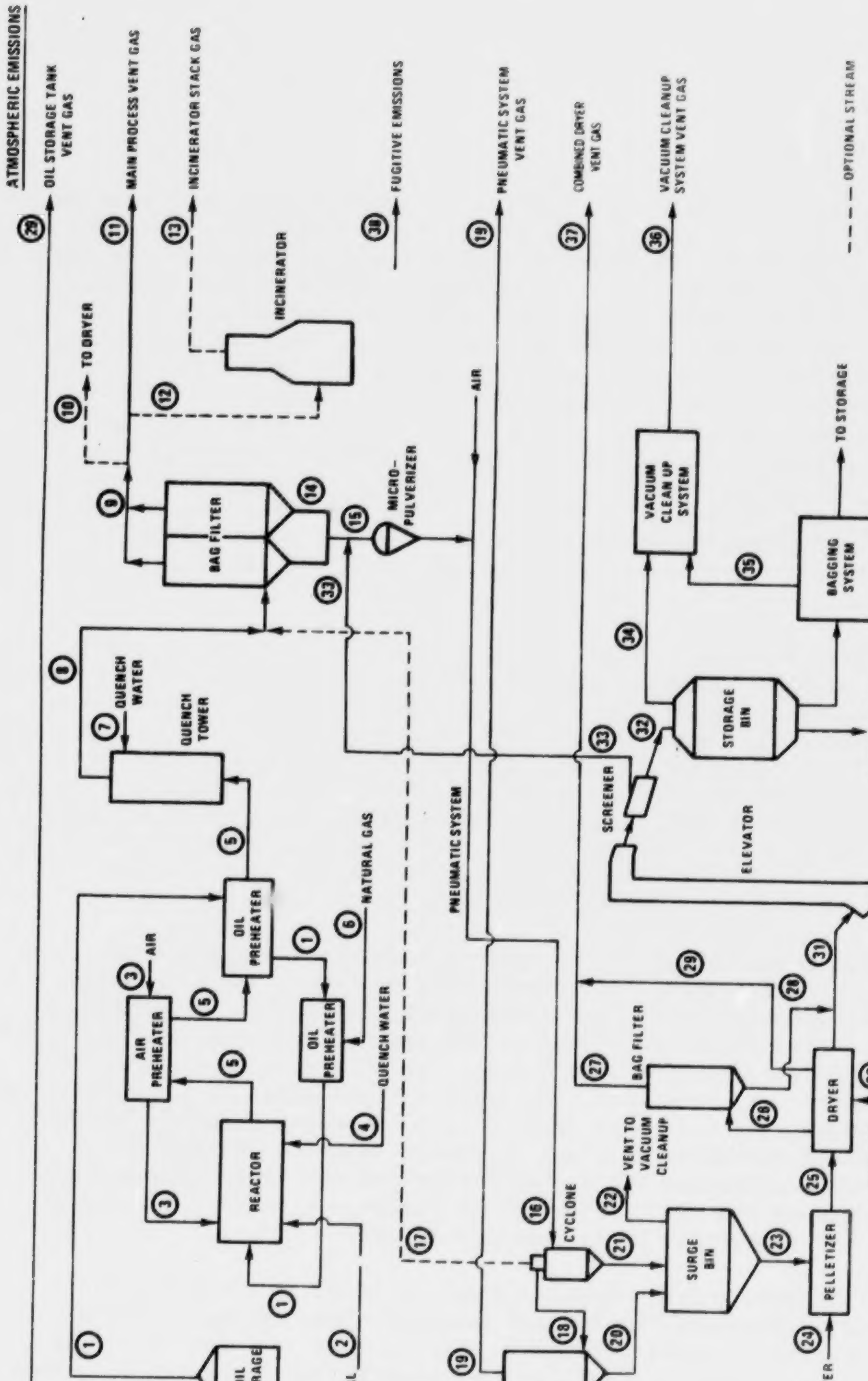

Figure 5.3-1. Flow diagram for the oil furnace carbon black process.

TABLE 5.3-1. STREAM IDENTIFICATION FOR THE OIL FURNACE PROCESS (Figure 5.3-1)

Stream	Identification
1	Oil feed
2	Natural gas feed
3	Air to reactor
4	Quench water
5	Reactor effluent
6	Gas to oil preheater
7	Water to quench tower
8	Quench tower effluent
9	Bag filter effluent
10	Vent gas purge for dryer fuel
11	Main process vent gas
12	Vent gas to incinerator
13	Incinerator stack gas
14	Recovered carbon black
15	Carbon black to micropulverizer
16	Pneumatic conveyor system
17	Cyclone vent gas recycle
18	Cyclone vent gas
19	Pneumatic system vent gas
20	Carbon black from bag filter
21	Carbon black from cyclone
22	Surge bin vent
23	Carbon black to pelletizer
24	Water to pelletizer
25	Pelletizer effluent
26	Dryer direct heat source vent
27	Dryer heat exhaust after bag filter
28	Carbon black from dryer bag filter
29	Dryer indirect heat source vent
30	Hot gases to dryer
31	Dried carbon black
32	Screened carbon black
33	Carbon black recycle
34	Storage bin vent gas
35	Bagging system vent gas
36	Vacuum cleanup system vent gas
37	Combined dryer vent gas
38	Fugitive emissions
39	Oil storage tank vent gas

is used as a fuel to heat a second reactor. When the first reactor becomes too cool to crack the natural gas feed, the positions of the reactors are reversed, and the second reactor is used to crack the gas while the first is heated. Normally, more than enough hydrogen is produced to make the thermal black process self-sustaining, and the surplus hydrogen is used to fire boilers that supply process steam and electric power.

The collected thermal black is pulverized and pelletized to a final product in much the same manner as is furnace black. Thermal process yields are generally high (35 to 60 percent), but the relatively coarse particles produced, 180 to 470 nm, do not have the strong reinforcing properties required for rubber products.

5.3.2 Emissions and Controls

5.3.2.1 Oil Furnace Process - Emissions from carbon black manufacture include particulate matter, carbon monoxide, organics, nitrogen oxides, sulfur compounds, polycyclic organic matter (POM) and trace elements.

The principal source of emissions in the oil furnace process is the main process vent. The vent stream consists of the reactor effluent and the quench water vapor vented from the carbon black recovery system. Gaseous emissions may vary considerably, according to the grade of carbon black being produced. Organic and CO emissions tend to be higher for small particle production, corresponding with the lower yields obtained. Sulfur compound emissions are a function of the feed sulfur content. Tables 5.3-2 and 5.3-3 show the normal emission ranges to be expected, with typical average values.

The combined dryer vent (stream 37 in Figure 5.3-1) emits carbon black from the dryer bag filter and contaminants from the use of the main process vent gas if the gas is used as a supplementary fuel for the dryer. It also emits contaminants from the combustion of impurities in the natural gas fuel for the dryer. These contaminants include sulfur oxides, nitrogen oxides, and the unburned portion of each of the species present in the main process vent gas (see Table 5.3-2). The oil feedstock storage tanks are a source of organic emissions. Carbon black emissions also occur from the pneumatic transport system vent, the plantwide vacuum cleanup system vent, and from cleaning, spills and leaks (fugitive emissions).

Gaseous emissions from the main process vent may be controlled with CO boilers, incinerators or flares. The pellet dryer combustion furnace, which is, in essence, a thermal incinerator, may also be employed in a control system. CO boilers, thermal incinerators or combinations of these devices can achieve essentially complete oxidation of organics and can oxidize sulfur compounds in the process flue gas. Combustion efficiencies of 99.6 percent for hydrogen sulfide and 99.8 percent for carbon monoxide have been measured for a flare on a carbon black plant. Particulate emissions may also be reduced by combustion of some of the carbon black particles, but emissions of sulfur dioxide and nitrogen oxides are thereby increased.

5.3.2.2 Thermal Process - Emissions from the furnaces in this process are very low because the offgas is recycled and burned in the next furnace to provide heat for cracking, or sent to a boiler as fuel. The carbon black is recovered in a bag filter between the two furnaces.

The rest is recycled in the offgas. Some adheres to the surface of the checkerbrick where it is burned off in each firing cycle.

Emissions from the dryer vent, the pneumatic transport system vent, the vacuum cleanup system vent, and fugitive sources are similar to those for the oil furnace process, since the operations which give rise to these emissions in the two processes are similar. There is no emission point in the thermal process which corresponds to the oil storage tank vents in the oil furnace process. Also in the thermal process, sulfur compounds, POM, trace elements and organic compound emissions are negligible, because low sulfur natural gas is used, and the process offgas is burned as fuel.

TABLE 5.3-2. EMISSION FACTORS FOR CHEMICAL SUBSTANCES FROM OIL FURNACE CARBON BLACK MANUFACTURE[a]

Chemical substance	Main process vent gas[b]	
	kg/Mg	lb/ton
Carbon disulfide	30	60
Carbonyl sulfide	10	20
Methane	25 (10-60)	50 (20-120)
Nonmethane VOC		
Acetylene	45 (5-130)	90 (10-260)
Ethane	0^c	0^c
Ethylene	1.6	3.2
Propylene	0^c	0^c
Propane	0.23	0.46
Isobutane	0.10	0.20
n-Butane	0.27	0.54
n-Pentane	0^c	0^c
POM	0.002	0.004
Trace elements[d]	< 0.25	< 0.50

[a] Expressed in terms of weight of emissions per unit weight of carbon black produced.

[b] These chemical substances are emitted only from the main process vent. Average values are based on six sampling runs made at a representative plant (Reference 1). Ranges given in parentheses are based on results of a survey of operating plants (Reference 4).

[c] Below detection limit of 1 ppm.

[d] Beryllium, lead, mercury, among several others.

TABLE 5.3-3. EMISSION FACTORS

EMISSION FACTOR

Process	Particulate[b]		Carbon Monoxide		Nitrogen Oxides	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Oil furnace process						
Main process vent	3.27[d] (0.1-5)	6.53[d] (0.2-10)	1,400[e] (700-2,200)	2,800[e] (1,400-4,400)	0.28[e] (1-2.8)	0.56[e] (2-5.6)
Flare	1.35 (1.2-1.5)	2.70 (2.4-3)	122 (108-137)	245 (216-274)	NA	NA
CO boiler and incinerator	1.04	2.07	0.88	1.75	4.65	9.3
Combined Dryer vent						
Bag filter[h]	0.12 (0.01-0.40)	0.24 (0.02-0.80)			0.36 (0.12-0.61)	0.73 (0.24-1.22)
Scrubber[h]	0.36 (0.01-0.70)	0.71 (0.02-1.40)			1.10	2.20
Pneumatic system vent[h]						
Bag filter	0.29 (0.06-0.70)	. 0.58 (0.12-1.40)				
Oil storage tank vent[i]						
Uncontrolled						
Vacuum cleanup system vent[h]						
Bag filter	0.03 (0.01-0.05)	0.06 (0.02-0.10)				
Fugitive emissions[h]	0.10	0.20				
Solid waste incinerator[j]	0.12	0.24	0.01	0.02	0.04	0.08
Thermal process[k]	Neg	Neg	Neg	Neg	Unknown[l]	Unknown[l]

---

[a] Expressed in terms of weight of emissions per unit weight of carbon black produced. Blanks indicate no emissions. Most plants use bag filters on all process trains for product recovery except solid waste incineration. Some plants may use scrubbers on at least one process train. NA = not available.

[b] The particulate matter is carbon black.

[c] Emission factors do not include organic sulfur compounds which are reported separately in Table 5.3-2. Individual organic species comprising the nonmethane VOC emissions are included in Table 5.3-.2

[d] Average values based on surveys of plants (References 4-5).

[e] Average values based on results of 6 sampling runs conducted at a representative plant with a mean production rate of 5.1 x 10 Mg/yr (5.6 x 10 ton/yr). Ranges of values are based on a survey of 15 plants (Reference 4). Controlled by bag filter.

[f] Not detected at detection limit of 1 ppm.

FOR CARBON BLACK MANUFACTURE[a]

RATING: C

Sulfur Oxides		Methane		Nonmethane VOC[c]		Hydrogen Sulfide	
kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
$0^{e,f}$ (0-12)	$0^{e,f}$ (0-24)	25^{e} (10-60)	50^{e} (20-120)	50^{e} (10-159)	100^{e} (20-300)	30^{e} $5S-13S^{g}$	60^{e} $10S-26S^{g}$
25 (21.9-28)	50 (44-56)			1.85 (1.7-2)	3.7 (3.4-4)	1	2
17.5	35.2			0.99	1.98	0.11	0.22
0.26 (0.03-0.54)	0.52 (0.06-1.08)						
0.20	0.40						
				0.72	1.44		
0.01	0.02			0.01	0.02		
Neg	Neg			Neg	Neg	Neg	Neg

---

[g] S is the weight percent sulfur in the feed.

[h] Average values and corresponding ranges of values are based on a survey of plants (Reference 4) and on the public files of Louisiana Air Control Commission.

[i] Emission factor calculated using empirical correlations for petrochemical losses from storage tanks (vapor pressure = 0.7 kPa). Emissions are mostly aromatic oils.

[j] Based on emission rates obtained from the National Emissions Data System. All plants do not use solid waste incineration. See Section 2.1.

[k] Emissions from the furnaces are negligible. Emissions from the dryer vent, pneumatic system vent and vacuum cleanup system and fugitive sources are similar to those for the oil furnace process.

[l] Data are not available.

References for Section 5.3

1. R. W. Serth and T. W. Hughes, Source Assessment: Carbon Black Manufacture, EPA-600/2-77-107k, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1977.

2. Air Pollutant Emission Factors, APTD-0923, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1970.

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5. K. C. Hustvedt and L. B. Evans, Standards Support and Emission Impact Statement: An Investigation of the Best Systems of Emission Reduction for Furnace Process Carbon Black Plants in the Carbon Black Industry (Draft), U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1976.

6. Source Testing of a Waste Heat Boiler, EPA-75-CBK-3, U. S. Environmental Protection Agency, Research Triangle Park, NC, January 1975.

7. R. W. Gerstle and J. R. Richards, Industrial Process Profiles for Environmental Use, Chapter 4: Carbon Black Industry, EPA-600-2-77-023d, U. S. Environmental Protection Agency, Cincinnati, OH, February 1977.

8. G. D. Rawlings and T. W. Hughes, "Emission Inventory Data for Acrylonitrile, Phthalic Anhydride, Carbon Black, Synthetic Ammonia, and Ammonium Nitrate", Proceedings of APCA Specialty Conference on Emission Factors and Inventories, Anaheim, CA, November 13-16, 1978.

5.4 CHARCOAL

5.4.1 Process Description[1-3]

Charcoal is the solid carbon residue following the pyrolysis (carbonization or destructive distillation) of carbonaceous raw materials. Principal raw materials are medium to dense hardwoods such as beech, birch, hard maple, hickory and oak. Others are softwoods (primarily long leaf and slash pine), nutshells, fruit pits, coal, vegetable wastes and paper mill residues. Charcoal is used primarily as a fuel for outdoor cooking. In some instances, its manufacture may be considered as a solid waste disposal technique. Many raw materials for charcoal manufacture are wastes, as noted, and charcoal manufacture is also used in forest management for disposal of refuse.

Recovery of acetic acid and methanol byproducts was initially responsible for stimulation of the charcoal industry. As synthetic production of these chemicals became commercialized, recovery of acetic acid and methanol became uneconomical.

Charcoal manufacturing can be generally classified into either batch (45 percent) or continuous operations (55 percent). Batch units such as the Missouri type charcoal kiln (Figure 5.4-1) are small manually loaded and unloaded kilns producing typically 16 megagrams (17.6 tons) of charcoal during a three week cycle. Continuous units (i.e., multiple hearth furnaces) produce an average of 2.5 megagrams (2.75 tons) per hour of charcoal. During the manufacturing process, the wood is heated, driving off water and highly volatile organic compounds (VOC). Wood temperature rises to approximately 275°C (527°F), and VOC distillate yield increases. At this point, external application of heat is no longer required, since the carbonization reactions become exothermic. At 350°C (662°F), exothermic pyrolysis ends, and heat is again applied to remove the less volatile tarry materials from the product charcoal.

Fabrication of briquets from raw material may be either an integral part of a charcoal producing facility, or an independent operation, with charcoal being received as raw material. Charcoal is crushed, mixed with a binder solution, pressed and dried to produce a briquet of approximately 90 percent charcoal.

5.4.2 Emissions and Controls[3-9]

There are five types of charcoal products, charcoal; noncondensible gases (carbon monoxide, carbon dioxide, methane and ethane); pyroacids (primarily acetic acid and methanol); tars and heavy oils; and water. Products and product distribution are varied, depending on raw materials and carbonization parameters. The extent to which organics and carbon monoxide are naturally combusted before leaving the retort varies from plant to plant. If uncombusted, tars may solidify to form particulate emissions, and pyroacids may form aerosol emissions.

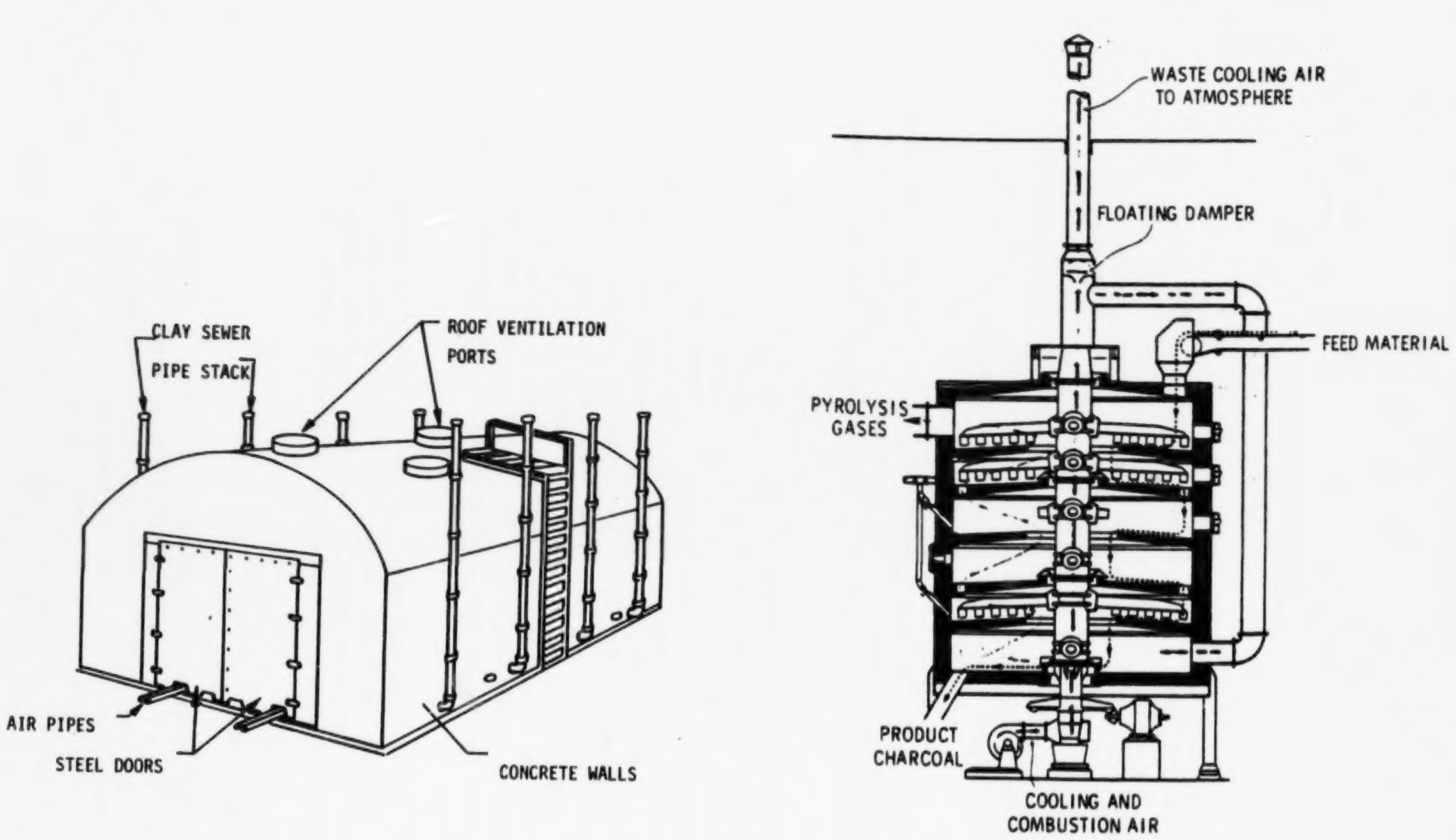


Figure 5.4-1. The Missouri type charcoal kiln (left) and the multiple hearth furnace (right).

Control of emissions from batch type charcoal kilns is difficult because of the cyclic nature of the process and, therefore, its emissions. Throughout a cycle, both the emission composition and flow rate change. Batch kilns do not typically have emission control devices, but some may use afterburners. Continuous production of charcoal is more amenable to emission control than are batch kilns, since emission composition and flow rate are relatively constant. Afterburning is estimated to reduce emissions of particulates, carbon monoxide and VOC by at least 80 percent.

Briquetting operations can control particulate emissions with centrifugal collection (65 percent control) or fabric filtration (99 percent control).

Uncontrolled emission factors for the manufacture of charcoal are shown in Table 5.4-1.

TABLE 5.4-1. UNCONTROLLED EMISSION FACTORS FOR CHARCOAL MANUFACTURING[a]

EMISSION FACTOR RATING: C

Pollutant	Charcoal Manufacturing		Briquetting	
	kg/Mg	lb/ton	kg/Mg	lb/ton
Particulate[b]	133	266	28	56
Carbon monoxide[c]	172	344	-	-
Nitrogen oxides[d]	12	24	-	-
VOC				
Methane[e]	52	104	-	-
Nonmethane[f]	157	314	-	-

[a] Expressed as weight per unit charcoal produced. Dash = not applicable. Reference 3. Afterburning is estimated to reduce emissions of particulates, carbon monoxide and VOC > 80%. Briquetting operations can control particulate emissions with centrifugal collection (65% control) or fabric filtration (99% control).

[b] Includes tars and heavy oils (References 1, 5-9). Polycyclic organic matter (POM) carried by suspended particulates was determined to average 4.0 mg/kg (Reference 6).

[c] References 1, 5, 9.

[d] Reference 3 (Based on 0.14% wood nitrogen content).

[e] References 1, 5, 7, 9.

[f] References 1, 3, 5, 7. Consists of both noncondensibles (ethane, formaldehyde, unsaturated hydrocarbons) and condensibles (methanol, acetic acid, pyroacids).

References for Section 5.4

1. Air Pollutant Emission Factors, APTD-0923, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1970.
2. R. N. Shreve, Chemical Process Industries, Third Edition, McGraw-Hill Book Company, New York, 1967.
3. C. M. Moscowitz, Source Assessment: Charcoal Manufacturing State of the Art, EPA-600/2-78-004z, U. S. Environmental Protection Agency, Cincinnati, OH, December 1978.
4. Riegel's Handbook of Industrial Chemistry, Seventh Edition, J. A. Kent, ed., Van Nostrand Reinhold Company, New York, 1974.
5. J. R. Hartwig, "Control of Emissions from Batch-type Charcoal Kilns", Forest Products Journal, 21(9):49-50, April 1971.
6. W. H. Maxwell, Stationary Source Testing of a Missouri-type Charcoal Kiln, EPA-907/9-76-001, U. S. Environmental Protection Agency, Kansas City, MO, August 1976.
7. R. W. Rolke, et al., Afterburner Systems Study, EPA-RZ-72-062, U. S. Environmental Protection Agency, Research Triangle Park, NC, August 1972.
8. B. F. Keeling, Emission Testing the Missouri-type Charcoal Kiln, Paper 76-37.1, Presented at the 69th Annual Meeting of the Air Pollution Control Association, Portland, OR, June 1976.
9. P. B. Hulman, et al., Screening Study on Feasibility of Standards of Performance for Wood Charcoal Manufacturing, EPA Contract No. 68-02-2608, Radian Corporation, Austin, TX, August 1978.

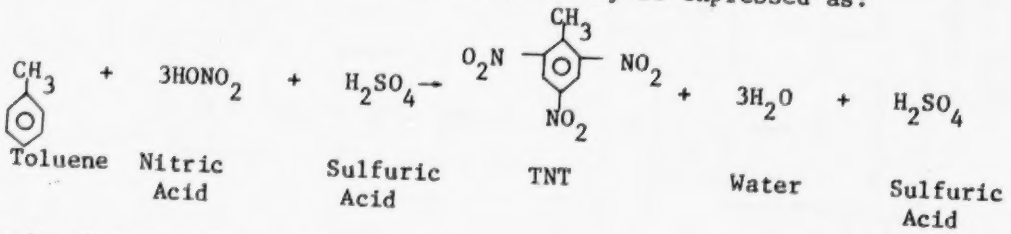
5.6 EXPLOSIVES

5.6.1 General[1]

An explosive is a material that, under the influence of thermal or mechanical shock, decomposes rapidly and spontaneously with the evolution of large amounts of heat and gas. There are two major categories, high explosives and low explosives. High explosives are further divided into initiating, or primary, high explosives and secondary high explosives. Initiating high explosives are very sensitive and are generally used in small quantities in detonators and percussion caps to set off larger quantities of secondary high explosives. Secondary high explosives, chiefly nitrates, nitro compounds and nitramines, are much less sensitive to mechanical or thermal shock, but they explode with great violence when set off by an initiating explosive. The chief secondary high explosives manufactured for commercial and military use are ammonium nitrate blasting agents and 2,4,6,-trinitrotoluene (TNT). Low explosives, such as black powder and nitrocellulose, undergo relatively slow autocombustion when set off and evolve large volumes of gas in a definite and controllable manner. Many different types of explosives are manufactured. As examples of high and low explosives, the production of TNT and nitrocellulose (NC) are discussed below.

5.6.2 TNT Production[1-3,6]

TNT may be prepared by either a continuous or a batch process, using toluene, nitric acid and sulfuric acid as raw materials. The production of TNT follows the same chemical process, regardless of whether batch or continuous method is used. The flow chart for TNT production is shown in Figure 5.6-1. The overall chemical reaction may be expressed as:



The production of TNT by nitration of toluene is a three stage process performed in a series of reactors, as shown in Figure 5.6-2. The mixed acid stream is shown to flow counter current to the flow of the organic stream. Toluene and spent acid fortified with a 60 percent HNO_3 solution are fed into the first reactor. The organic layer formed in the first reactor is pumped into the second reactor, where it is subjected to further nitration with acid from the third reactor fortified with additional HNO_3. The product from the second nitration step, a mixture of all possible isomers of dinitrotoluene (DNT), is pumped to the third reactor. In the final reaction, the DNT is treated with a fresh feed of nitric acid and oleum (a solution of SO_3[sulfur trioxide] in anhydrous sulfuric acid). The crude TNT from this third nitration consists primarily of 2,4,6-trinitrotoluene. The crude TNT is

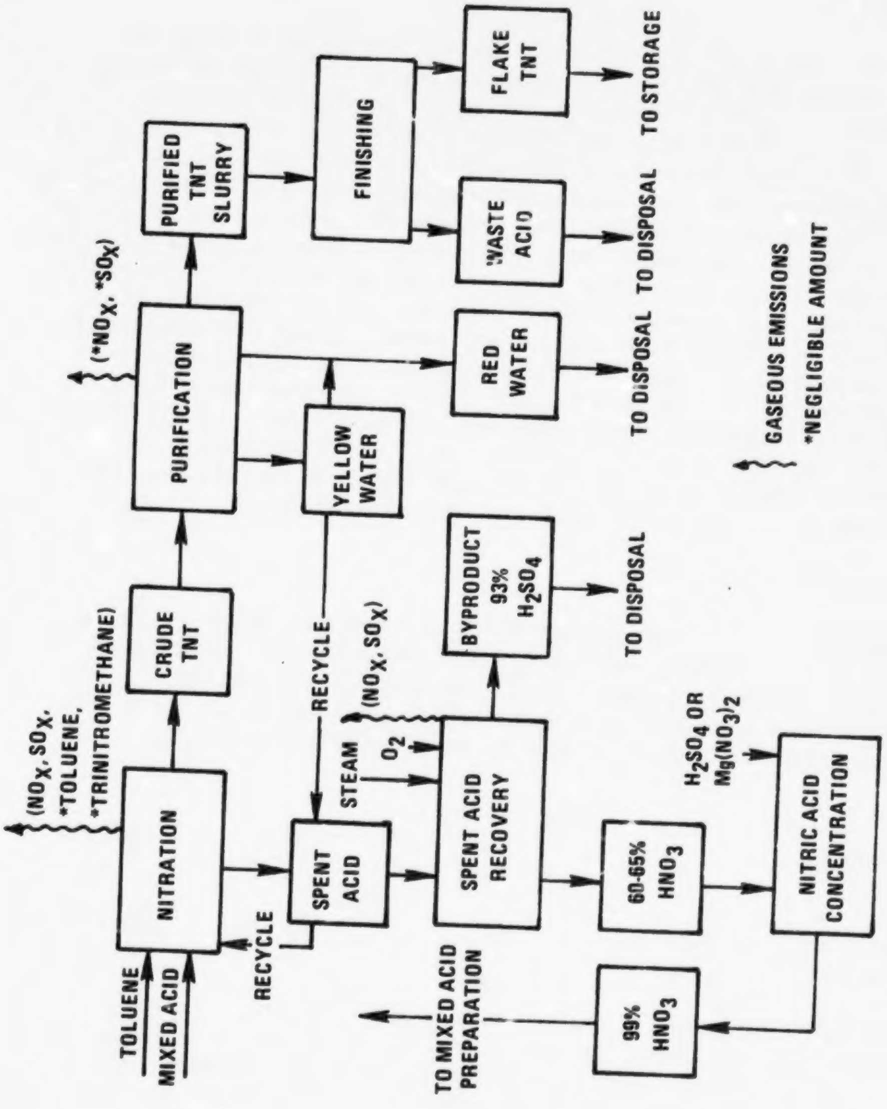


Figure 5.6-1. TNT production.

washed to remove free acid, and the wash water (yellow water) is recycled to the early nitration stages. The washed TNT is then neutralized with soda ash and treated with a 16 percent aqueous sodium sulfite (Sellite) solution to remove contaminating isomers. The Sellite waste solution (red water) from the purification process is discharged directly as a liquid waste stream, is collected and sold, or is concentrated to a slurry and incinerated. Finally, the TNT crystals are melted and passed through hot air dryers, where most of the water is evaporated. The dehydrated product is solidified, and the TNT flakes packaged for transfer to a storage or loading area.

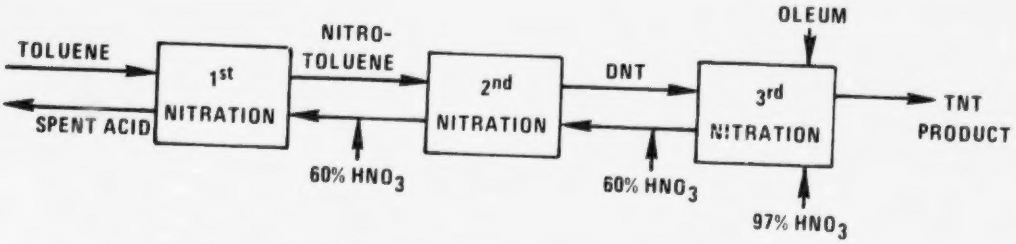


Figure 5.6-2. Nitration of toluene to form trinitrotoluene.

5.6.3 Nitrocellulose Production[1,6]

Nitrocellulose is commonly prepared by the batch type mechanical dipper process. A newly developed continuous nitration processing method is also being used. In batch production, cellulose in the form of cotton linters, fibers or specially prepared wood pulp is purified by boiling and bleaching. The dry and purified cotton linters or wood pulp are added to mixed nitric and sulfuric acid in metal reaction vessels known as dipping pots. The reaction is represented by:

$$\underset{\text{Cellulose}}{(C_6H_7O_2(OH)_3)_x} + \underset{\text{Nitric Acid}}{3HONO_2} + \underset{\text{Sulfuric Acid}}{H_2SO_4} \rightarrow \underset{\text{Nitrocellulose}}{(C_6H_7O_2(ONO_2)_3)_x} + \underset{\text{Water}}{3H_2O} + \underset{\text{Sulfuric Acid}}{H_2SO_4}$$

Following nitration, the crude NC is centrifuged to remove most of the spent nitrating acids and is put through a series of water washing and boiling treatments to purify the final product.

TABLE 5.6-1. EMISSION FACTORS FOR THE OPEN BURNING OF TNT[a,b]
(lb pollution/ton TNT burned)

Type of Explosive	Particulates	Nitrogen Oxides	Carbon Monoxide	Volatile Organic Compounds
TNT	180.0	150.0	56.0	1.1

[a] Reference 7. Particulate emissions are soot. VOC is nonmethane.

[b] The burns were made on very small quantities of TNT, with test apparatus designed to simulate open burning conditions. Since such test simulations can never replicate actual open burning, it is advisable to use the factors in this Table with caution.

TABLE 5.6-2. EMISSION FACTORS FOR

EMISSION FACTOR

Process	Particulates		Sulfur oxides (SO_2)	
	kg/Mg	lb/ton	kg/Mg	lb/ton
TNT - Batch Process[c]				
Nitration reactors				
Fume recovery	–	–	–	–
Acid recovery	–	–	–	–
Nitric acid concentrators	–	–	–	–
Sulfuric acid concentrators[d]				
Electrostatic precipitator (exit)	–	–	7 (2 - 20)	14 (4 - 40)
Electrostatic precipitator w/scrubber[e]	–	–	Neg.	Neg.
Red water incinerator				
Uncontrolled[f]	12.5 (0.015 - 63)	25 (0.03 - 126)	1 (0.025 - 1.75)	2 (0.05 - 3.5)
Wet scrubber[g]	0.5	1	1 (0.025 - 1.75)	2 (0.05 - 3.5)
Sellite exhaust	–	–	29.5 (0.005 - 88)	59 (0.01 - 177)
TNT - Continuous Process[h]				
Nitration reactors				
Fume recovery	–	–	–	–
Acid recovery	–	–	–	–
Red water incinerator	0.13 (0.015 - 0.25)	0.25 (0.03 - 0.5)	0.12 (0.025 - 0.22)	0.24 (0.05 - 0.43)
Nitrocellulose[h]				
Nitration reactors[i]	–	–	0.7 (0.4 - 1)	1.4 (0.8 - 2)
Nitric acid concentrator	–	–	–	–
Sulfuric acid concentrator	–	–	34 (0.2 - 67)	68 (0.4-135)
Boiling tubs	–	–	–	–

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[a] For some processes, considerable variations in emissions have been reported. Average of reported values is shown first, ranges in parentheses. Where only one number is given, only one source test was available. Emission factors are in units of kg of pollutant per Mg and pounds of pollutant per ton of TNT or Nitrocellulose produced.

[b] Significant emissions of volatile organic compounds have not been reported for the explosives industry. However, negligible emissions of toluene and trinitromethane (TNM) from nitration reactors have been reported in TNT manufacture. Also, fugitive VOC emissions may result from various solvent recovery operations. See Reference 6.

[c] Reference 5.

[d] Acid mist emissions influenced by nitrobody levels and type of furnace fuel.

[e] No data available for NO_x emissions after scrubber. NO_x emissions are assumed unaffected by scrubber.

EXPLOSIVES MANUFACTURING[a,b]

RATING: C

Nitrogen oxides (NO_2) kg/Mg	Nitrogen oxides (NO_2) lb/ton	Nitric acid mist (100% HNO_3) kg/Mg	Nitric acid mist (100% HNO_3) lb/ton	Sulfuric acid mist (100% H_2SO_4) kg/ton	Sulfuric acid mist (100% H_2SO_4) lb/ton
12.5 (3 - 19)	25 (6 - 38)	0.5 (0.15 - 0.95)	1 (0.3 - 1.9)	–	–
27.5 (0.5 - 68)	55 (1 - 136)	46 (0.005 - 137)	92 (0.02 - 275)	–	–
18.5 (8 - 36)	37 (16 - 72)	–	–	4.5 (0.15 - 13.5)	9 (0.3 - 27)
20 (1 - 40)	40 (2 - 80)	–	–	32.5 (0.5 - 94)	65 (1 - 188)
20 (1 - 40)	40 (2 - 80)	–	–	2.5 (2 - 3)	5 (4 - 6)
13 (0.75 - 50)	26 (1.5 - 101)	–	–	–	–
2.5	5	–	–	–	–
–	–	–	–	3 (0.3 - 8)	6 (0.6 - 16)
4 (3.35 - 5)	8 (6.7 - 10)	0.5 (0.15 - 0.95	1 (0.3 - 1.9)	–	–
1.5 (0.5 - 2.25)	3 (1 - 4.5)	0.01 (0.005 - 0.015)	0.02 (0.01 - 0.03)	–	–
3.5 (3 - 4.2)	7 (6.1 - 8.4)	–	–	–	–
7 (1.85 - 17)	14 (3.7 - 34)	9.5 (0.25 - 18)	19 (0.5 - 36)	–	–
7 (5 - 9)	14 (10 - 18)	–	–	–	–
–	–	–	–	0.3	0.6
1	2	–	–	–	–

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[f] Use low end of range for modern efficient units, high end for less efficient units.

[g] Apparent reductions in NO_x and particulate after control may not be significant, because these values are based on only one test result.

[h] Reference 4.

[i] For product with low nitrogen content (12%), use high end of range. For products with higher nitrogen content, use lower end of range.

5.6.4 Emissions and Controls[2-3,5-7]

Oxides of nitrogen (NO_x) and sulfur (SO_x) are the major emissions from the processes involving the manufacture, concentration and recovery of acids in the nitration process of explosives manufacturing. Emissions from the manufacture of nitric and sulfuric acid are discussed in other Sections of this publication. Trinitromethane (TNM) is a gaseous byproduct of the nitration process of TNT manufacture. Volatile organic compound emissions result primarily from fugitive vapors from various solvent recovery operations. Explosive wastes and contaminated packaging material are regularly disposed of by open burning, and such results in uncontrolled emissions, mainly of NO_x and particulate matter. Experimental burns of several explosives to determine "typical" emission factors for the open burning of TNT are presented in Table 5.6-1.

In the manufacture of TNT, emissions from the nitrators containing NO, NO_2, N_2O, trinitromethane (TNM) and some toluene are passed through a fume recovery system to extract NO_x as nitric acid, and then are vented through scrubbers to the atmosphere. Final emissions contain quantities of unabsorbed NO_x and TNM. Emissions may also come from the production of Sellite solution and the incineration of red water. Red water incineration results in atmospheric emissions of NO_x, SO_2 and ash (primarily Na_2SO_4.)

In the manufacture of nitrocellulose, emissions from reactor pots and centrifuge are vented to an NO_x water absorber. The weak HNO_3 solution is transferred to the acid concentration system. Absorber emissions are mainly NO_x. Another possible source of emissions is the boiling tubs, where steam and acid vapors vent to the absorber.

The most important fact affecting emissions from explosives manufacture is the type and efficiency of the manufacturing process. The efficiency of the acid and fume recovery systems for TNT manufacture will directly affect the atmospheric emissions. In addition, the degree to which acids are exposed to the atmosphere during the manufacturing process affects the NO_x and SO_x emissions. For nitrocellulose production, emissions are influenced by the nitrogen content and the desired product quality. Operating conditions will also affect emissions. Both TNT and nitrocellulose can be produced in batch processes. Such processes may never reach steady state, and emission concentrations may vary considerably with time, and fluctuations in emissions will influence the efficiency of control methods.

Several measures may be taken to reduce emissions from explosive manufacturing. The effects of various control devices and process changes, along with emission factors for explosives manufacturing, are shown in Table 5.6-2. The emission factors are all related to the amount of product produced and are appropriate either for estimating long term emissions or for evaluating plant operation at full production conditions. For short time periods, or for plants with intermittent operating schedules, the emission factors in Table 5.6-2 should be used with caution, because processes not associated with the nitration step are often not in operation at the same time as the nitration reactor.

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1. R. N. Shreve, Chemical Process Industries, 3rd Ed., McGraw-Hill Book Company, New York, 1967.
2. Unpublished data on emissions from explosives manufacturing, Office of Criteria and Standards, National Air Pollution Control Administration, Durham, NC, June 1970.
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5. Air Pollution Engineering Source Sampling Surveys, Volunteer Army Ammunition Plant and Joliet Army Ammunition Plant, U. S. Army Environmental Hygiene Agency, Edgewood Arsenal, MD, July 1967, July 1968.
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5.10 PAINT AND VARNISH

5.10.1 Paint Manufacturing[1]

The manufacture of paint involves the dispersion of a colored oil or pigment in a vehicle, usually an oil or resin, followed by the addition of an organic solvent for viscosity adjustment. Only the physical processes of weighing, mixing, grinding, tinting, thinning and packaging take place. No chemical reactions are involved.

These processes take place in large mixing tanks at approximately room temperature.

The primary factors affecting emissions from paint manufacture are care in handling dry pigments, types of solvents used and mixing temperature. About 1 or 2 percent of the solvent is lost even under well controlled conditions. Particulate emissions amount to 0.5 to 1.0 percent of the pigment handled.

Afterburners can reduce emitted volatile organic compounds (VOC) by 99 percent and particulates by about 90 percent. A water spray and oil filter system can reduce particulate emissions from paint blending by 90 percent.

5.10.2 Varnish Manufacturing[1-3,5]

The manufacture of varnish also involves the mixing and blending of various ingredients to produce a wide range of products. However in this case, chemical reactions are initiated by heating. Varnish is cooked in either open or enclosed gas fired kettles for periods of 4 to 16 hours at temperatures of 93 to 340°C (200 to 650°F).

Varnish cooking emissions, largely in the form of volatile organic compounds, depend on the cooking temperatures and times, the solvent used, the degree of tank enclosure and the type of air pollution controls used. Emissions from varnish cooking range from 1 to 6 percent of the raw material.

To reduce organic compound emissions from the manufacture of paint and varnish, control techniques include condensers and/or adsorbers on solvent handling operations, and scrubbers and afterburners on cooking operations. Afterburners can reduce volatile organic compounds by 99 percent. Emission factors for paint and varnish are shown in Table 5.10-1.

TABLE 5.10-1. UNCONTROLLED EMISSION FACTORS FOR PAINT AND VARNISH MANUFACTURING[a,b]

EMISSION FACTOR RATING: C

Type of product	Particulate		Nonmethane VOC[c]	
	kg/Mg pigment	lb/ton pigment	kg/Mg of product	lb/ton of product
Paint[d]	10	20	15	30
Varnish				
Bodying oil	-	-	20	40
Oleoresinous	-	-	75	150
Alkyd	-	-	80	160
Acrylic	-	-	10	20

[a] References 2, 4-8.

[b] Afterburners can reduce VOC emissions by 99% and particulates by about 90%. A water spray and oil filter system can reduce particulates by about 90%.

[c] Expressed as undefined organic compounds whose composition depends upon the type of solvents used in the manfacture of paint and varnish.

[d] Reference 4. Particulate matter (0.5 - 1.0 %) is emitted from pigment handling.

References for Section 5.10

1. Air Pollutant Emission Factors, APTD-0923, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1970.

2. R. L. Stenburg, "Controlling Atmospheric Emissions from Paint and Varnish Operations, Part I", Paint and Varnish Production, September 1959.

3. Private Communication between Resources Research, Inc., Reston, VA, and National Paint, Varnish and Lacquer Association, Washington, DC., September 1969.

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5. Air Pollution Engineering Manual, Second Edition, AP-40, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1973.

6. E. G. Lunche, et al., "Distribution Survey of Products Emitting Organic Vapors in Los Angeles County", Chemical Engineering Progress, 53(8):371-376, August 1957.

7. Communication on emissions from paint and varnish operations between Resources Research, Inc., Reston, VA, and G. Sallee, Midwest Research Institute, Kansas City, MO, December 17, 1969.

8. Communication between Resources Research, Inc., Reston, VA, and Roger Higgins, Benjamin Moore Paint Company, June 25, 1968.

5.12 PHTHALIC ANHYDRIDE

5.12.1 General[1]

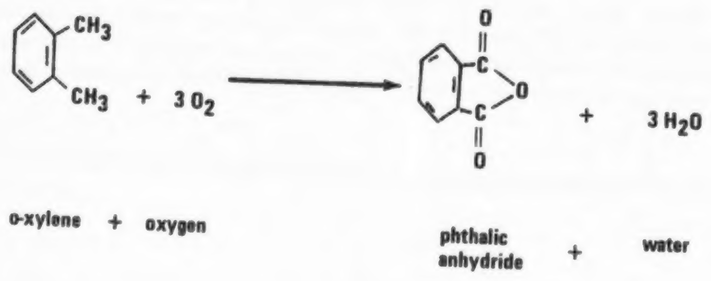
Phthalic anhydride (PAN) production in the United States in 1972 was 0.9 billion pounds per year; this total is estimated to increase to 2.2 billion pounds per year by 1985. Of the current production, 50 percent is used for plasticizers, 25 percent for alkyd resins, 20 percent for unsaturated polyester resins, and 5 percent for miscellaneous and exports. PAN is produced by catalytic oxidation of either ortho-xylene or naphthalene. Since naphthalene is a higher priced feedstock and has a lower feed utilization (about 1.0 lb PAN/lb o-xylene versus 0.97 lb PAN/lb naphthalene), future production growth is predicted to utilize o-xylene. Because emission factors are intended for future as well as present application, this report will focus mainly on PAN production utilizing o-xylene as the main feedstock.

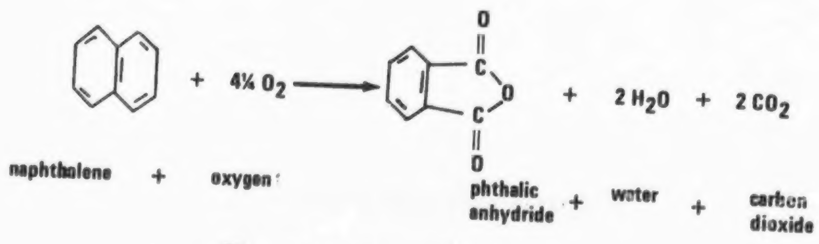
The processes for producing PAN by o-xylene or naphthalene are the same except for reactors, catalyst handling, and recovery facilities required for fluid bed reactors.

In PAN production using o-xylene as the basic feedstock, filtered air is preheated, compressed, and mixed with vaporized o-xylene and fed into the fixed-bed tubular reactors. The reactors contain the catalyst, vanadium pentoxide, and are operated at 650 to 725°F (340 to 385°C). Small amounts of sulfur dioxide are added to the reactor feed to maintain catalyst activity. Exothermic heat is removed by a molten salt bath circulated around the reactor tubes and transferred to a steam generation system.

Naphthalene-based feedstock is made up of vaporized naphthalene and compressed air. It is transferred to the fluidized bed reactor and oxidized in the presence of a catalyst, vanadium pentoxide, at 650 to 725°F (340 to 385°C). Cooling tubes located in the catalyst bed remove the exothermic heat which is used to produce high-pressure steam. The reactor effluent consists of PAN vapors, entrained catalyst, and various by-products and non-reactant gas. The catalyst is removed by filtering and returned to the reactor.

The chemical reactions for air oxidation of o-xylene and naphthalene are as follows.





The reactor effluent containing crude PAN plus products from side reactions and excess oxygen passes to a series of switch condensers where the crude PAN cools and crystallizes. The condensers are alternately cooled and then heated, allowing PAN crystals to form and then melt from the condenser tube fins.

The crude liquid is transferred to a pretreatment section in which phthalic acid is dehydrated to anhydride. Water, maleic anhydride, and benzoic acid are partially evaporated. The liquid then goes to a vacuum distillation section where pure PAN (99.8 wt. percent pure) is recovered. The product can be stored and shipped either as a liquid or a solid (in which case it is dried, flaked, and packaged in multi-wall paper bags). Tanks for holding liquid PAN are kept at 300°F (150°C) and blanketed with dry nitrogen to prevent the entry of oxygen (fire) or water vapor (hydrolysis to phthalic acid).

Maleic anhydride is currently the only by-product being recovered.

Figures 1 and 2 show the process flow for air oxidation of o-xylene and naphthalene, respectively.

5.12.2 Emissions and Controls[1]

Emissions from o-xylene and naphthalene storage are small and presently are not controlled.

The major contributor of emissions is the reactor and condenser effluent which is vented from the condenser unit. Particulate, sulfur oxides (for o-xylene-based production), and carbon monoxide make up the emissions, with carbon monoxide comprising over half the total. The most efficient (96 percent) system of control is the combined usage of a water scrubber and thermal incinerator. A thermal incinerator alone is approximately 95 percent efficient in combustion of pollutants for o-xylene-based production, and 80 percent efficient for naphthalene-based production. Thermal incinerators with steam generation show the same efficiencies as thermal incinerators alone. Scrubbers have a 99 percent efficiency in collecting particulates, but are practically ineffective in reducing carbon monoxide emissions. In naphthalene-based production, cyclones can be used to control catalyst dust emissions with 90 to 98 percent efficiency.

Pretreatment and distillation emissions—particulates and hydrocarbons—are normally processed through the water scrubber and/or incinerator used for the main process stream (reactor and condenser) or scrubbers alone, with the same efficiency percentages applying.

Product storage in the liquid phase results in small amounts of gaseous emissions. These gas streams can either be sent to the main process vent gas control devices or first processed through sublimation boxes or devices used to recover escaped PAN. Flaking and bagging emissions are negligible, but can be sent to a cyclone for recovery of PAN dust. Exhaust from the cyclone presents no problem.

Table 5.12-1 gives emission factors for controlled and uncontrolled emissions from the production of PAN.

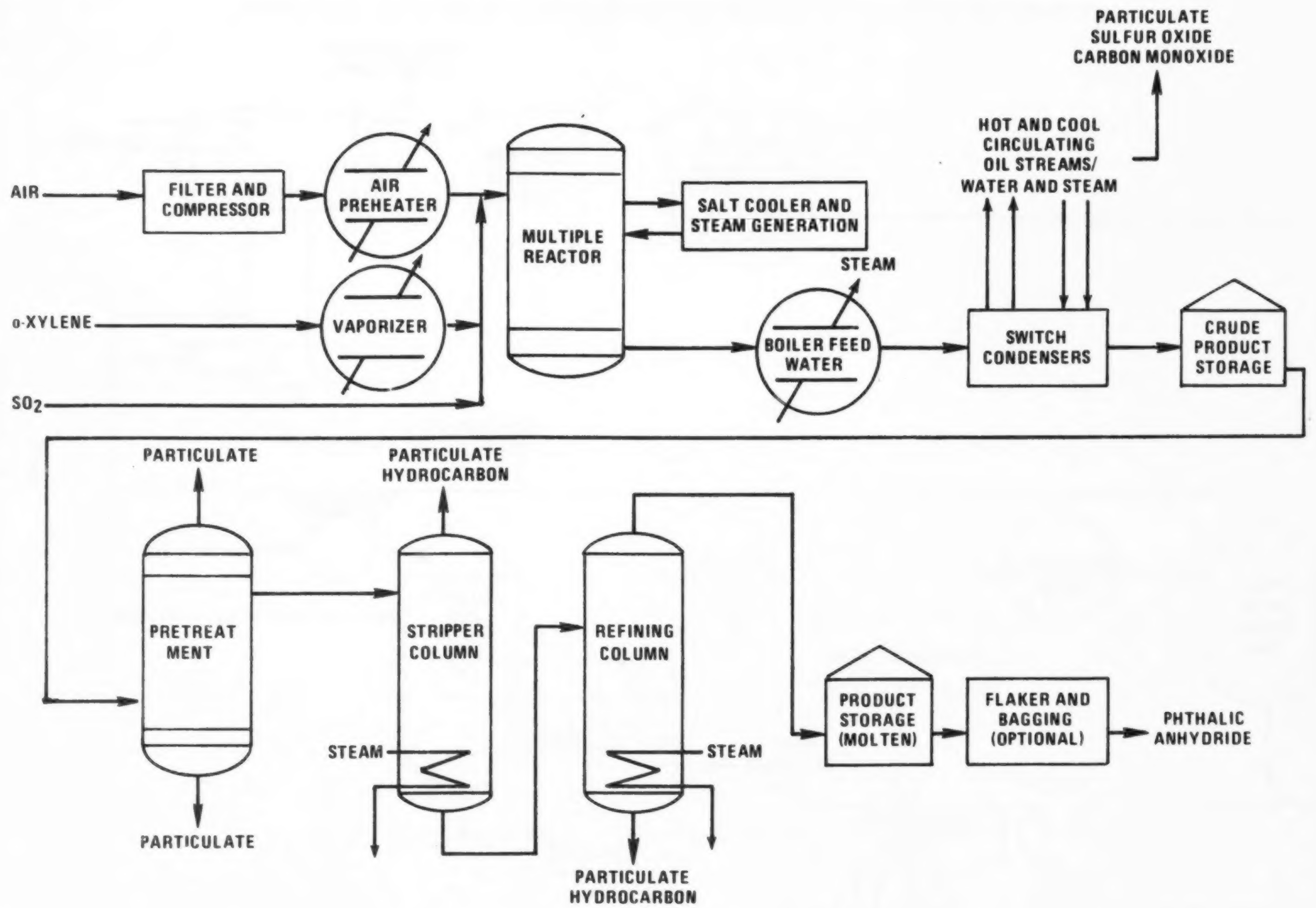


Figure 5.12-1. Flow diagram for phthalic anhydride using o-xylene as basic feedstock.[1]

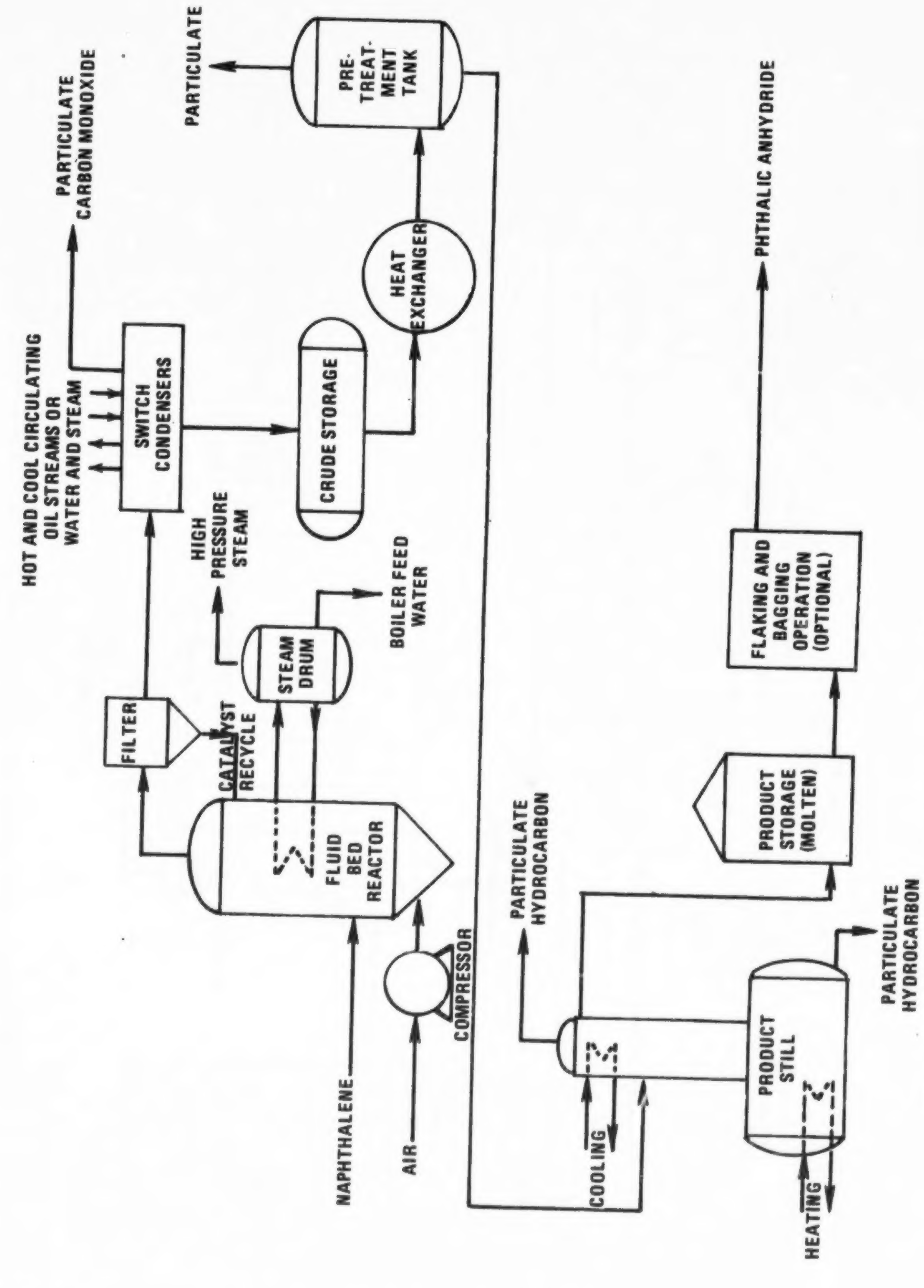


Figure 5.12-2. Flow diagram for phthalic anhydride using naphthalene as basic feedstock.[1]

TABLE 5.12-1. EMISSION FACTORS FOR PHTHALIC ANHYDRIDE[a]

EMISSION FACTOR RATING: B

	Particulate		SO_x		Nonmethane VOC[b]		CO	
Process	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Oxidation of o-xylene[c]								
Main process stream[d]								
Uncontrolled	69[e]	138[e]	4.7[f]	9.4[f]	0	0	151	301
W/scrubber and thermal incinerator	3	6	4.7	9.4	0	0	6	12
W/thermal incinerator	4	7	4.7	9.4	0	0	8	15
W/incinerator with steam generator	4	7	4.7	9.4	0	0	8	15
Pretreatment								
Uncontrolled	6.4[g]	13[g]	0	0	0	0	0	0
W/scrubber and thermal incinerator	0.3	0.5	0	0	0	0	0	0
W/thermal incinerator	0.4	0.7	0	0	0	0	0	0
Distillation								
Uncontrolled	45[e]	89[e]	0	0	1.2[e,h]	2.4[e,h]	0	0
W/scrubber and thermal incinerator	2	4	0	0	<0.1	<0.1	0	0
W/thermal incinerator	2	4	0	0	<0.1	0.1	0	0
Oxidation of naphthalene[c]								
Main process stream[d]								
Uncontrolled	28[i,k]	56[i,k]	0	0	0	0	50	100
W/thermal incinerator	6	11	0	0	0	0	10	20
W/scrubber	0.3	0.6	0	0	0	0	50	100
Pretreatment								
Uncontrolled	2.5[j]	5[j]	0	0	0	0	0	0
W/thermal incinerator	0.5	1	0	0	0	0	0	0
W/scrubber	<0.1	<0.1	0	0	0	0	0	0
Distillation								
Uncontrolled	19[i]	38[i]	0	0	5[h,i]	10[h,i]	0	0
W/thermal incinerator	4	8	0	0	1	2	0	0
W/scrubber	0.2	0.4	0	0	<0.1	0.1	0	0

[a] Reference 1. Factors are in kg of pollutant/Mg (lb/ton) of phthalic anhydride produced.

[b] Emissions contain no methane.

[c] Control devices listed are those currently being used by phthalic anhydride plants.

[d] Main process stream includes reactor and multiple switch condensers as vented through condenser unit.

[e] Consists of phthalic anhydride, maleic anhydride, benzoic acid.

[f] Value shown corresponds to relatively fresh catalyst, which can change with catalyst age. Can be 9.5 - 13 kg/Mg (19 - 25 lb/ton) for aged catalyst.

[g] Consists of phthalic anhydride and maleic anhydride.

[h] Normally a vapor, but can be present as a particulate at low temperature.

[i] Consists of phthalic anhydride, maleic anhydride, naphthaquinone.

[j] Particulate is phthalic anhydride.

[k] Does not include catalyst dust, controlled by cyclones with efficiency of 90 - 98%.

Reference for Section 5.12

1. Engineering and Cost Study of Air Pollution Control for the Petrochemical Industry, Vol. 7: Phthalic Anhydride Manufacture from Ortho-xylene, EPA-450/3-73-006g, U. S. Environmental Protection Agency, Research Triangle Park, NC, July 1975.

5.14 PRINTING INK

5.14.1 Process Description[1]

There are four major classes of printing ink: letterpress and lithographic inks, commonly called oil or paste inks; and flexographic and rotogravure inks, which are referred to as solvent inks. These inks vary considerably in physical appearance, composition, method of application, and drying mechanism. Flexographic and rotogravure inks have many elements in common with the paste inks but differ in that they are of very low viscosity, and they almost always dry by evaporation of highly volatile solvents.[2]

There are three general processes in the manufacture of printing inks: (1) cooking the vehicle and adding dyes, (2) grinding of a pigment into the vehicle using a roller mill, and (3) replacing water in the wet pigment pulp by an ink vehicle (commonly known as the flushing process).[3] The ink "varnish" or vehicle is generally cooked in large kettles at 200° to 600°F (93° to 315°C) for an average of 8 to 12 hours in much the same way that regular varnish is made. Mixing of the pigment and vehicle is done in dough mixers or in large agitated tanks. Grinding is most often carried out in three-roller or five-roller horizontal or vertical mills.

5.14.2 Emissions and Controls[1,4]

Varnish or vehicle preparation by heating is by far the largest source of ink manufacturing emissions. Cooling the varnish components – resins, drying oils, petroleum oils, and solvents – produces odorous emissions. At about 350°F (175°C) the products begin to decompose, resulting in the emission of decomposition products from the cooking vessel. Emissions continue throughout the cooking process with the maximum rate of emissions occuring just after the maximum temperature has been reached. Emissions from the cooking phase can be reduced by more than 90 percent with the use of scrubbers or condensers followed by afterburners.[4,5]

Compounds emitted from the cooking of oleoresinous varnish (resin plus varnish) include water vapor, fatty acids, glycerine, acrolein, phenols, aldehydes, ketones, terpene oils, terpenes, and carbon dioxide. Emissions of thinning solvents used in flexographic and rotogravure inks may also occur.

The quantity, composition, and rate of emissions from ink manufacturing depend upon the cooking temperature and time, the ingredients, the method of introducing additives, the degree of stirring, and the extent of air or inert gas blowing. Particulate emissions resulting from the addition of pigments to the vehicle are affected by the type of pigment and its particle size. Emission factors for the manufacture of printing ink are presented in Table 5.14-1.

TABLE 5.14-1. EMISSION FACTORS FOR PRINTING INK MANUFACTURING[a]

EMISSION FACTOR RATING: E

Type of process	Nonmethane volatile organic compounds[b] kg/Mg of product	Nonmethane volatile organic compounds[b] lb/ton of product	Particulates kg/Mg of pigment	Particulates lb/ton of pigment
Vehicle cooking				
General	60	120	NA	NA
Oils	20	40	NA	NA
Oleoresinous	75	150	NA	NA
Alkyds	80	160	NA	NA
Pigment mixing	NA	NA	1	2

[a] Based on data from Section 5.10, Paint and Varnish. NA = not applicable.

[b] The nonmethane VOC emissions are a mix of volatilized vehicle components, cooking decomposition products and ink solvent.

References for Section 5.14

1. Air Pollutant Emission Factors, APTD-0923, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1970.
2. R. N. Shreve, Chemical Process Industries, 3rd Ed., New York, McGraw Hill Book Co., 1967.
3. L. M. Larsen, Industrial Printing Inks, New York, Reinhold Publishing Company, 1962.
4. Air Pollution Engineering Manual, 2nd Edition, AP-40, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1973.
5. Private communication with Ink Division of Interchemical Corporation, Cincinnati, Ohio, November 10, 1969.

5.15 SOAP AND DETERGENTS

5.15.1 Soap Manufacture

Process Description[1,7] - Soap may be manufactured by either a batch or continuous process, using either the alkaline saponification of natural fats and oils or the direct saponification of fatty acids. The kettle, or full boiled, process is a batch process of several steps in either a single kettle or a series of kettles. Fats and oils are saponified by live steam boiling in a caustic solution, followed by "graining", or precipitating, the soft curds of soap out of the aqueous lye solution by adding sodium chloride (salt). The soap solution then is washed to remove glycerine and color body impurities, to leave the "neat" soap to form during a settling period. Continuous alkaline saponification of natural fats and oils follows the same steps as batch processing, but it eliminates the need for a lengthy process time. Direct saponification of fatty acids is also accomplished in continuous processes. Fatty acids obtained by continuous hydrolysis usually are continuously neutralized with caustic soda in a high speed mixer/neutralizer to form soap.

All soap is finished for consumer use in such various forms as liquid, powder, granule, chip, flake or bar.

Emissions and Controls[7] - The main atmospheric pollution problem in the manufacture of soap is odor. Vent lines, vacuum exhausts, product and raw material storage, and waste streams are all potential odor sources. Control of these odors may be achieved by scrubbing all exhaust fumes and, if necessary, incinerating the remaining compounds. Odors emanating from the spray drier may be controlled by scrubbing with an acid solution.

Blending, mixing, drying, packaging and other physical operations are subject to dust emissions. The production of soap powder by spray drying is the largest single source of dust in the manufacture of soap. Dust emissions from finishing operations other than spray drying can be controlled by dry filters and baghouses. The large size of the particulates in soap drying means that high efficiency cyclones installed in series can be satisfactory in controlling emissions.

5.15.2 Detergent Manufacture

Process Description[1,7-8] - The manufacture of spray dried detergent has three main processing steps, slurry preparation, spray drying and granule handling. Figure 5.15-1 illustrates the various operations. Detergent slurry is produced by blending liquid surfactant with powdered and liquid materials (builders and other additives) in a closed mixing tank called a crutcher. Liquid surfactant used in making the detergent slurry is produced by the sulfonation or sulfation by sulfuric acid of a linear alkylate or a fatty acid, which is then neutralized with caustic solution (NaOH). The blended slurry is held in a surge vessel for continuous pumping to the spray dryer. The slurry is sprayed at high pressure through nozzles into a vertical drying tower having a stream of hot air of from 315° to 400°C (600° to 750°F). Most towers designed for detergent production are countercurrent, with slurry introduced at the top and heated

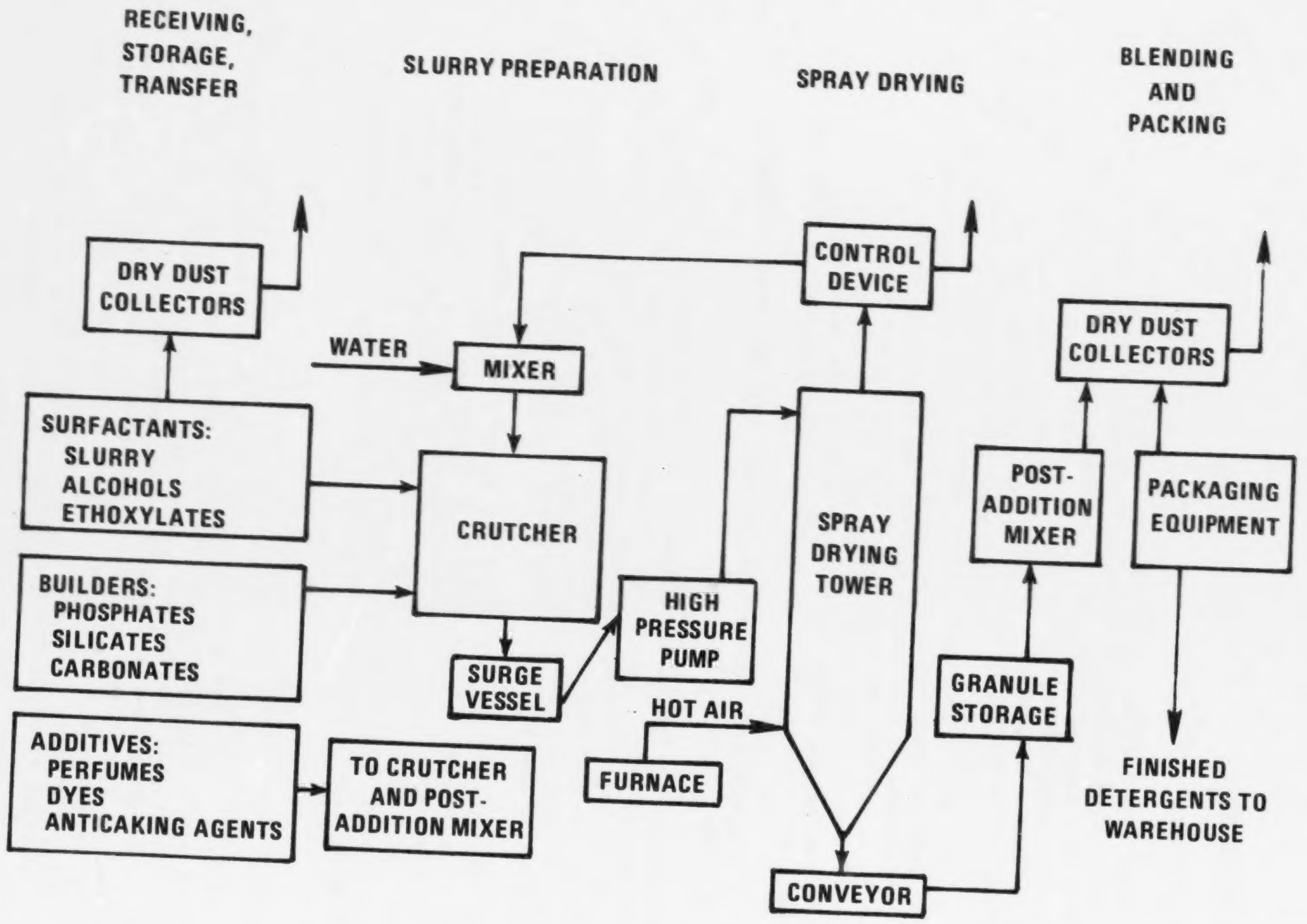


Figure 5.15-1. Manufacture of spray dried detergents.

air introduced at the bottom. A few towers are concurrent and have both hot air and slurry introduced at the top. The detergent granules are mechanically or air conveyed from the tower to a mixer to incorporate additional dry or liquid ingredients and finally sent to packaging and storage.

Emissions and Controls[7-8] - In the batching and mixing of fine dry ingredients to form slurry, dust emissions are generated at scale hoppers, mixers and the crutcher. Baghouses and/or fabric filters are used not only to reduce or to eliminate the dust emissions but to recover raw materials. The spray drying operation is the major source of particulate emissions from detergent manufacturing. Particulate emissions from spray drying operations are shown in Table 5.15-1. There is also a minor source of volatile organics when the product being sprayed contains organic materials with low vapor pressures. These vaporized organic materials condense in the tower exhaust air stream into droplets or particles. Dry cyclones and cyclonic impingement scrubbers are the primary collection equipment employed to capture the detergent dust in the spray dryer exhaust for return to process. Dry cyclones are used in parallel or in series, to collect particulate (detergent dust) and to recycle the dry product back to the crutcher. Cyclonic impinged scrubbers are used in parallel to collect the particulate in a scrubbing slurry which is recycled back to the crutcher. Secondary collection equipment is used to collect the fine particulates that have escaped from the primary devices. Cyclonic impingement scrubbers are often followed by mist eliminators, and dry cyclones are followed by fabric filters or scrubber/electrostatic precipitator units. Conveying, mixing and packaging of detergent granules can cause dust emissions. Usually baghouses and/or fabric filters provide the best control.

TABLE 5.15-1. PARTICULATE EMISSION FACTORS FOR SPRAY DRYING DETERGENTS[a]

EMISSION FACTOR RATING: B

Control Device	Overall Efficiency, %	Particulate Emissions	
		kg/Mg of product	lb/ton of product
Uncontrolled	-	45	90
Cyclone[b]	85	7	14
Cyclone			
w/Spray chamber	92	3.5	7
w/Packed scrubber	95	2.5	5
w/Venturi scrubber	97	1.5	3

[a] References 2-6. Emissions data for volatile organic compounds has not been reported in the literature.

[b] Some type of primary collector, such as a cyclone, is considered an integral part of the spray drying system.

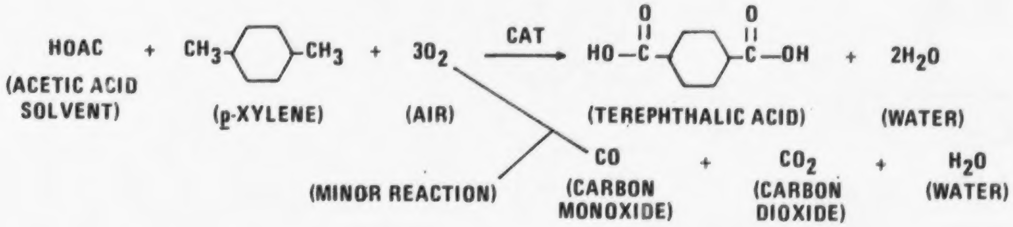
References for Section 5.15

1. *Air Pollutant Emission Factors*, APTD-0923, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1970.
2. A. H. Phelps, "Air Pollution Aspects of Soap and Detergent Manufacture", *Journal of the Air Pollution Control Association*, *17*(8):505-507, August 1967.
3. R. N. Shreve, *Chemical Process Industries*, Third Edition, New York, McGraw-Hill Book Company, 1967.
4. G. P. Larsen, *et al.*, "Evaluating Sources of Air Pollution", *Industrial and Engineering Chemistry*, *45*:1070-1074, May 1953.
5. P. Y. McCormick, *et al.*, "Gas-solid Systems", *Chemical Engineer's Handbook*, J. H. Perry (ed.), New York, McGraw-Hill Book Company, 1963.
6. Communication with Maryland State Department of Health, Baltimore, MD, November 1969.
7. J. A. Danielson, *Air Pollution Engineering Manual*, AP-40, U. S. Environmental Protection Agency, May 1973.
8. *Source Category Survey: Detergent Industry*, EPA-450/3-80-030, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1980.

5.21 Terephthalic Acid

5.21.1 Process Description[1]

Terephthalic acid (TPA) is made by air oxidation of p-xylene and requires purification for use in polyester fiber manufacture. A typical continuous process for the manufacture of crude terephthalic acid (C-TPA) is shown in Figure 5.21-1. The oxidation and product recovery portion essentially consists of the Mid-Century oxidation process, whereas the recovery and recycle of acetic acid and recovery of methyl acetate are essentially as practiced by dimethyl terephthalate (DMT) technology. The purpose of the DMT process is to convert the terephthalic acid contained in C-TPA to a form that will permit its separation from impurities. C-TPA is extremely insoluble in both water and most common organic solvents. Additionally, it does not melt, it sublimes. Some products of partial oxidation of p-xylene, such as p-toluic acid and p-formyl benzoic acid, appear as impurities in TPA. Methyl acetate is also formed in significant amounts in the reaction.



C-TPA Production

Oxidation of p-xylene - P-xylene (stream 1 of Figure 5.21-1), fresh acetic acid (2), a catalyst system, such as manganese or cobalt acetate and sodium bromide (3), and recovered acetic acid are combined into the liquid feed entering the reactor (5). Air (6), compressed to a reaction pressure of about 2000 kPa (290 psi), is fed to the reactor. The temperature of the exothermic reaction is maintained at about 200°C (392°F) by controlling the pressure at which the reaction mixture is permitted to boil and form the vapor stream leaving the reactor (7).

Inert gases, excess oxygen, CO, CO_2, and volatile organic compounds (VOC) (8) leave the gas/liquid separator and are sent to the high pressure absorber. This stream is scrubbed with water under pressure, resulting in a gas stream (9) of reduced VOC content. Part of the discharge from the high pressure absorber is dried and is used as a source of inert gas (IG), and the remainder is passed through a pressure control valve and a noise silencer before being discharged to the atmosphere through process vent A. The underflow (23) from the absorber is sent to the azeotrope still for recovery of acetic acid.

Crystallization and Separation - The reactor liquid containing TPA (10) flows to a series of crystallizers, where the pressure is relieved and the

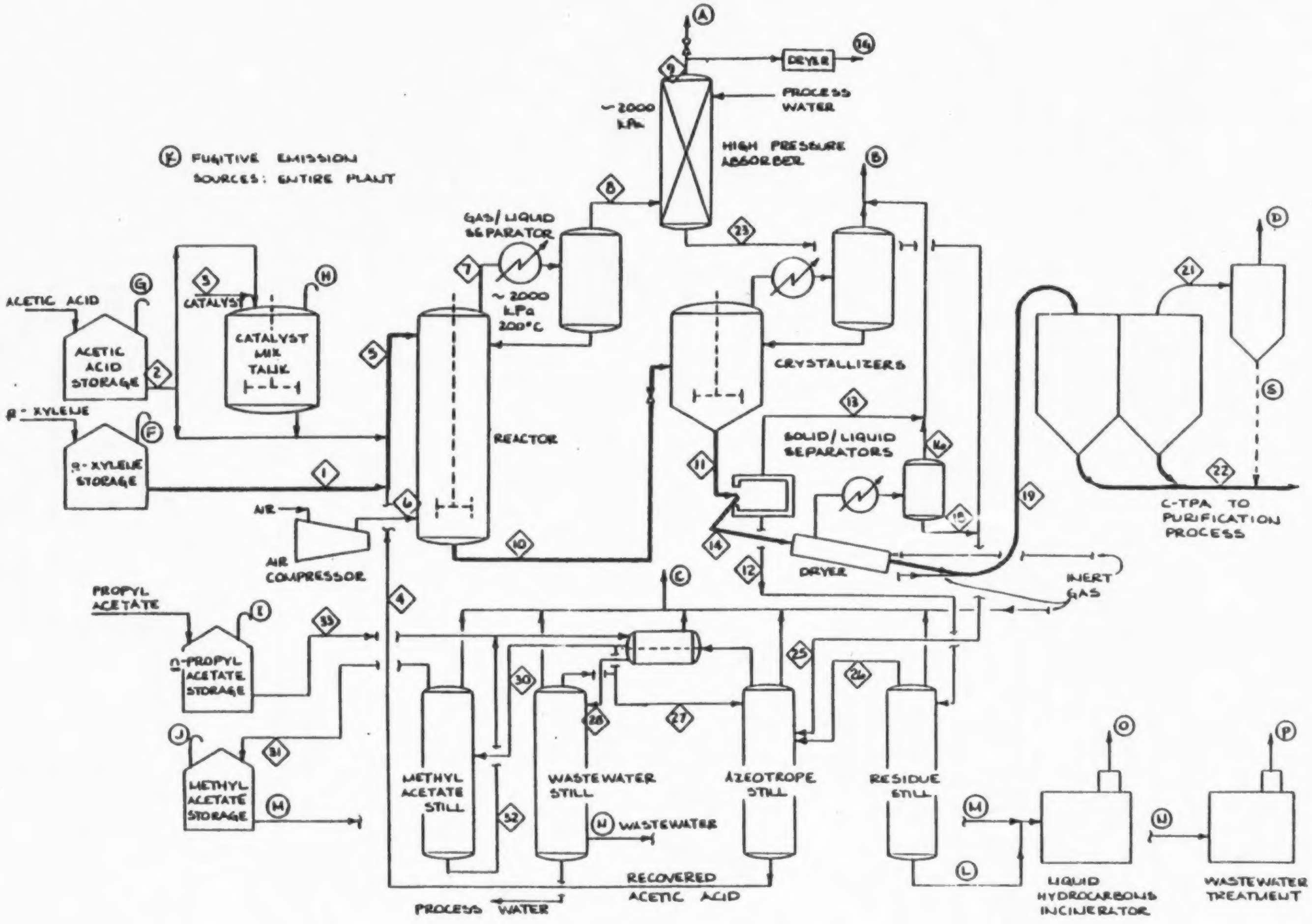


Figure 5.21-1. Crude Terephthalic Acid Process.

liquid is cooled by the vaporization and return of condensed VOC and water. The partially oxidized impurities are more soluble in acetic acid and tend to remain in solution, while TPA crystallizes from the liquor. The inert gas that was dissolved and entrained in the liquid under pressure is released when the pressure is relieved and is subsequently vented to the atmosphere along with the contained VOC (B). The slurry (11) from the crystallizers is sent to solid/liquid separators, where the TPA is recovered as a wet cake (14). The mother liquor (12) from the solid/liquid separators is sent to the distillation section, while the vent gas (13) is discharged to the atmosphere (B).

Drying, Handling and Storage - The wet cake (14) from solid/liquid separation is sent to dryers, where with the use of heat and IG, the moisture, predominately acetic acid, is removed, leaving the product, C-TPA, as dry free flowing crystals (19). IG is used to convey the product (19) to storage silos. The transporting gas (21) is vented from the silos to bag dust collectors to reduce its particulate loading, then is discharged to the atmosphere (D). The solids (S) from the bag filter can be forwarded to purification or can be incinerated.

Hot VOC laden IG from the drying operation is cooled to condense and recover VOC (18). The cooled IG (16) is vented to the atmosphere (B), and the condensate (stream 18) is sent to the azeotrope still for recovery of acetic acid.

Distillation and Recovery - The mother liquor (12) from solid/liquid separation flows to the residue still, where acetic acid, methyl acetate and water are recovered overhead (26) and product residues are discarded. The overhead (26) is sent to the azeotrope still where dry acetic acid is obtained by using n-propyl acetate as the water removing agent.

The aqueous phase (28) contains saturation amounts of n-propyl acetate and methyl acetate, which are stripped from the aqueous matter in the wastewater still. Part of the bottoms product is used as process water in absorption, and the remainder (N) is sent to wastewater treatment. A purge stream of the organic phase (30) goes to the methyl acetate still, where methyl acetate and saturation amounts of water are recovered as an overhead product (31) and are disposed of as a fuel (M). n-propyl acetate, obtained as the bottoms product (32), is returned to the azeotrope still. Process losses of n-propyl acetate are made up from storage (33). A small amount of inert gas, which is used for blanketing and instrument purging, is emitted to the atmosphere through vent C.

C-TPA Purification

The purification portion of the Mid-Century oxidation process involves the hydrogenation of C-TPA over a palladium containing catalyst at about 232°C (450°F). High purity TPA is recrystallized from a high pressure water solution of the hydrogenated material.

The Olin-Mathieson manufacturing process is similar to the Mid-Century process except the former uses 95 percent oxygen, rather than air, as the oxidizing agent. The final purification step consists essentially of a continuous sublimation and condensation procedure. The C-TPA is combined with small quantities of hydrogen and a solid catalyst, dispersed in steam, and transported to a furnace. There the C-TPA is vaporized and certain of the contained impurities are catalytically destroyed. Catalyst and nonvolatile impurities are removed in a series of filters, after which the pure TPA is condensed and transported to storage silos.

5.21.2 Emissions and Controls[1-3]

A general characterization of the atmospheric emissions from the production of C-TPA is difficult, because of the variety of processes. Emissions vary considerably, both qualitatively and quantitatively. The Mid-Century oxidation process appears to be one of the lowest polluters, and its predicted preeminence will suppress future emissions totals.

The reactor gas at vent A normally contains nitrogen (from air oxidation); unreacted oxygen; unreacted p-xylene; acetic acid (reaction solvent); carbon monoxide, carbon dioxide, and methyl acetate from oxidation of p-xylene and acetic acid not recovered by the high pressure absorber; and water. The quantity of VOC emitted at vent A can vary with absorber pressure and the temperature of exiting vent gases. During crystallization of terephthalic acid and separation of crystalized solids from the solvent (by centrifuge or filters), noncondensible gases carrying VOC are released. These vented gases and the C-TPA dryer vent gas are combined and released to the atmosphere at vent B. Different methods used in this process can affect the amounts of noncondensible gases and accompanying VOC emitted from this vent.

Gases released from the distillation section at vent C are the small amount of gases dissolved in the feed stream to distillation; the inert gas used in inert blanketing, instrument purging pressure control; and the VOC vapors carried by the noncondensable gases. The quantity of this discharge is usually small.

The gas vented from the bag filters on the product storage tanks (silos) (D) is dry, reaction generated inert gas containing the VOC not absorbed in the high pressure absorber. The vented gas stream contains a small quantity of TPA particulate that is not removed by the bag filters.

Performance of carbon adsorption control technology for a VOC gas stream similar to the reactor vent gas (A) and product transfer vent gas (D) has been demonstrated, but, carbon monoxide (CO) emissions will not be reduced. An alternative to the carbon adsorption system is a thermal oxidizer which provides reduction of both CO and VOC.

Emission sources and factors for the C-TPA process are presented in Table 5.21-1.

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TABLE 5.21-1. UNCONTROLLED EMISSION FACTORS FOR CRUDE TEREPHTHALIC ACID MANUFACTURE[a]

EMISSION FACTOR RATING: C

Emission Source	Stream Designation (Figure 5.21-1)	Emissions (g/kg)	
		Nonmethane VOC[b,c]	CO[c]
Reactor vent	A	15	17
Crystallization, separation, drying vent	B	1.9	-
Distillation and recovery vent	C	1.1	-
Product transfer vent[d]	D	1.8	2

[a] Factors are expressed as g of pollutant/kg of product produced. Dash = not applicable.

[b] Reference 1. VOC gas stream consists of methyl acetate, p-xylene, and acetic acid. No methane was found.

[c] Reference 1. Typically, thermal oxidation results in >99% reduction of VOC and CO. Carbon adsorption gives a 97% reduction of VOC only (Reference 1).

[d] Stream contains 0.7 g of TPA particulates/kg. VOC and CO emissions originated in reactor offgas (IG) used for transfer.

References for Section 5.21

1. S. W. Dylewski, Organic Chemical Manufacturing, Volume 7: Selected Processes, EPA-450/3-80-028b, U. S. Environmental Protection Agency, Research Triangle Park, NC, January 1981.

2. D. F. Durocher, et al., Screening Study To Determine Need for Standards of Performance for New Sources of Dimethyl Terephthalate and Terephthalic Acid Manufacturing, EPA Contract No. 68-02-1316, Radian Corporation, Austin, TX, July 1976.

3. J. W. Pervier, et al., Survey Reports on Atmospheric Emissions from the Petrochemical Industry, Volume II, EPA-450/3-73-005b, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1974.

5.24 MALEIC ANHYDRIDE

5.24.1 General[1]

The dominant end use of maleic anhydride (MA) is in the production of unsaturated polyester resins. These laminating resins, which have high structural strength and good dielectric properties, have a variety of applications in automobile bodies, building panels, molded boats, chemical storage tanks, lightweight pipe, machinery housings, furniture, radar domes, luggage and bathtubs. Other end products are fumaric acid, agricultural chemicals, alkyd resins, lubricants, copolymers, plastics, succinic acid, surface active agents, and more. In the United States, one plant uses only n-butane and another uses n-butane for 20 percent of its feedstock, but the primary raw material used in the production of MA is benzene. The MA industry is converting old benzene plants and building new plants to use n-butane. MA also is a byproduct of the production of phthalic anhydride. It is a solid at room temperature but is a liquid or gas during production. It is a strong irritant to skin, eyes and mucous membranes of the upper respiratory system.

The model MA plant, as described in this Section, has a benzene to MA conversion rate of 94.5 percent, has a capacity of 22,700 megagrams (25,000 tons) of MA produced per year, and runs 8000 hours per year.

Because of a lack of data on the n-butane process, this discussion covers only the benzene oxidation process.

5.24.2 Process Description[2]

Maleic anhydride is produced by the controlled air oxidation of benzene, illustrated by the following chemical reaction:

$$\underset{\text{Benzene}}{2\ C_6H_6} + \underset{\text{Oxygen}}{9\ O_2} \underset{\text{Catalyst}\ \longrightarrow}{\xrightarrow[MoO_3]{V_2O_5}} \underset{\substack{\text{Maleic}\\\text{anhydride}}}{2\ C_4H_2O_3} + \underset{\text{Water}}{H_2O} + \underset{\substack{\text{Carbon}\\\text{dioxide}}}{4\ CO_2}$$

Vaporized benzene and air are mixed and heated before entering the tubular reactor. Inside the reactor, the benzene/air mixture is reacted in the presence of a catalyst which contains approximately 70 percent vanadium pentoxide (V_2O_5), with usually 25 to 30 percent molybdenum trioxide (MoO_3), forming a vapor of MA, water and carbon dioxide. The vapor, which may also contain oxygen, nitrogen, carbon monoxide, benzene, maleic acid, formaldehyde, formic acid and other compounds from side reactions, leaves the reactor and is cooled and partially condensed so that about 40 percent of the MA is recovered in a crude liquid state. The effluent is then passed through a separator which directs the liquid to storage and the remaining vapor to the product recovery absorber. The absorber contacts the vapor with water, producing a liquid of about 40 percent maleic acid. The

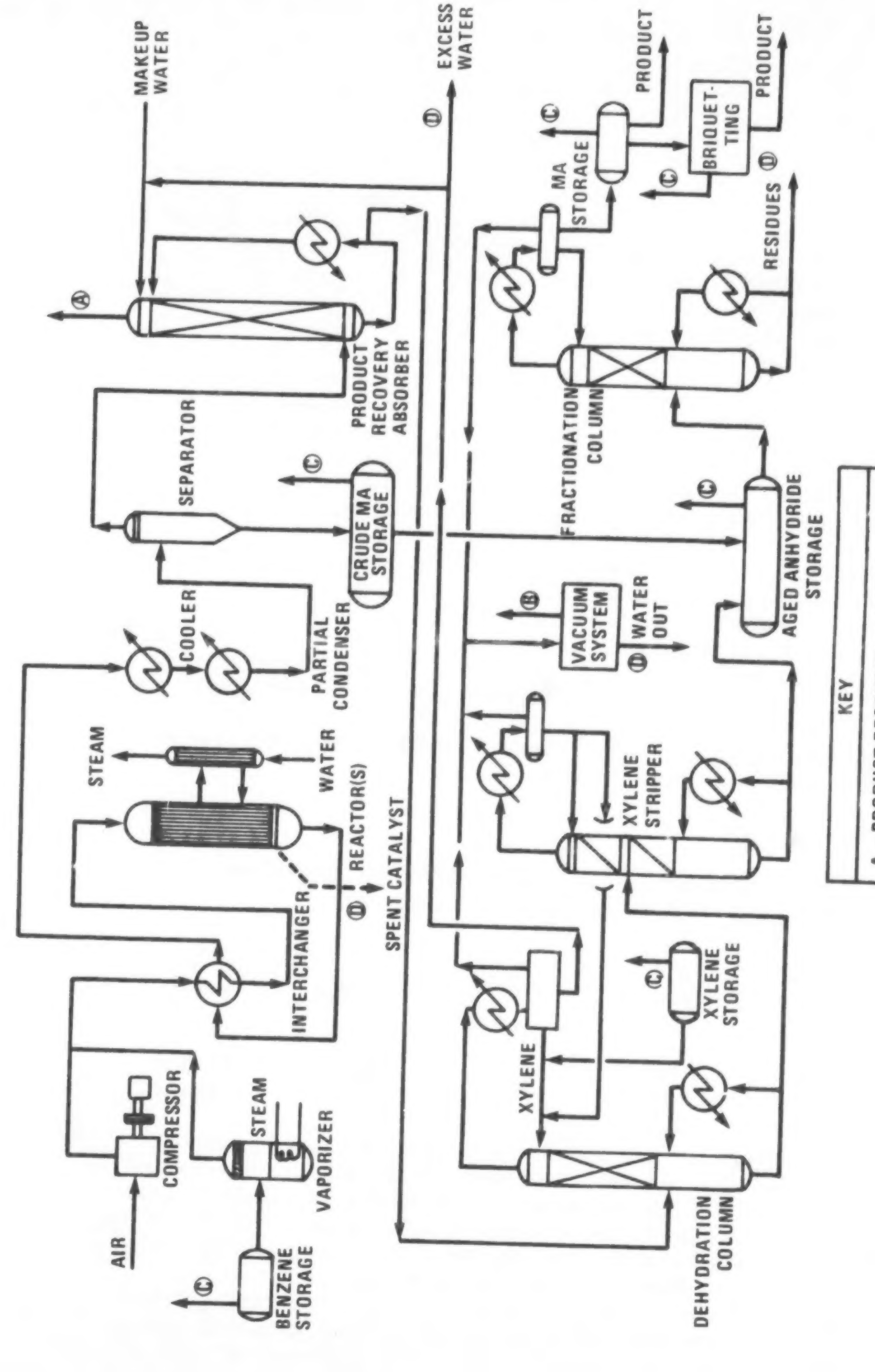

Figure 5.24-1. Process flow diagram for uncontrolled model plant.

40 percent mixture is converted to MA, usually by azeotropic distillation with xylene. Some processes may use a double effect vacuum evaporator at this point. The effluent then flows to the xylene stripping column where the xylene is extracted. This MA is then combined in storage with that from the separator. The molten product is aged to allow color forming impurities to polymerize. These are then removed in a fractionation column, leaving the finished product. Figure 5.24-1 represents a typical process.

MA product is usually stored in liquid form, although it is sometimes flaked and pelletized into briquets and bagged.

5.24.3 Emissions and Controls[2]

Nearly all emissions from MA production are from the main process vent of the product recovery absorber, the largest vent in the process. The predominant pollutant is unreacted benzene, ranging from 3 to 10 percent of the total benzene feed. The refining vacuum system vent, the only other exit for process emissions, produces 0.28 kilograms (0.62 lb) per hour of MA and xylene.

Fugitive emissions of benzene, xylene, MA and maleic acid also arise from the storage (see Section 4.3) and handling (see Section 9.1.3) of benzene, xylene and MA. Dust from the briquetting operations can contain MA, but no data are available on the quantity of such emissions.

TABLE 5.24-1. COMPOSITION OF UNCONTROLLED EMISSIONS FROM PRODUCT RECOVERY ABSORBER[a]

Component	Wt.%	kg/Mg	lb/ton
Nitrogen	73.37	21,406.0	42,812.0
Oxygen	16.67	4,863.0	9,726.0
Water	4.00	1,167.0	2,334.0
Carbon dioxide	3.33	972.0	1,944.0
Carbon monoxide	2.33	680.0	1,360.0
Benzene	0.33	67.0	134.0
Formaldehyde	0.05	14.4	28.8
Maleic acid	0.01	2.8	5.6
Formic acid	0.01	2.8	5.6
Total		29,175.0	58,350.0

[a] Reference 2.

Potential sources of secondary emissions are spent reactor catalyst, excess water from the dehydration column, vacuum system water, and fractionation column residues. The small amount of residual organics in the spent catalyst after washing has low vapor pressure and produces a small percentage of total emissions. Xylene is the principal organic contaminant in the excess water from the dehydration column and in the vacuum system water. The residues from the fractionation column are relatively heavy organics, with a molecular weight greater than 116, and they produce a small percentage of total emissions.

Benzene oxidation process emissions can be controlled at the main vent by means of carbon adsorption, thermal incineration or catalytic incineration. Benzene emissions can be eliminated by conversion to the n-butane process. Catalytic incineration and conversion from the benzene process to the n-butane process are not discussed for lack of data. The vent from the refining vacuum system is combined with that of the main process, as a control for refining vacuum system emissions. A carbon adsorption system or an incineration system can be designed and operated at a 99.5 percent removal efficiency for benzene and volatile organic compounds with the operating parameters given in Appendix D of Reference 2.

TABLE 5.24-2. EMISSION FACTORS FOR MALEIC ANHYDRIDE PRODUCTION[a]
EMISSION FACTOR RATING: C

Source	Nonmethane VOC[b]		Benzene	
	kg/Mg	lb/ton	kg/Mg	lb/ton
Product vents (recovery absorber and refining vacuum system combined vent)				
Uncontrolled	87	174	67.0	134.0
With carbon adsorption[c]	0.34	0.68	0.34	0.68
With incineration	0.43	0.86	0.34	0.68
Storage and handling emissions[d]	-	-	-	-
Fugitive emissions[e]	-	-	-	-
Secondary emissions[f]	N/A	N/A	N/A	N/A

[a] No data are available for catalytic incineration or for plants producing MA from n-butane. Dash: see footnote. N/A: not available.

[b] VOC also includes the benzene. For recovery absorber and refining vacuum, VOC can be MA and xylene; for storage and handling, MA, xylene and dust from briquetting operations; for secondary emissions, residual organics from spent catalyst, excess water from dehydration column, vacuum system water, and fractionation column residues. VOC contains no methane.

[c] Before exhaust gas stream goes into carbon adsorber, it is scrubbed with caustic to remove organic acids and water soluble organics. Benzene is the only likely VOC remaining.

[d] See Section 4.3.

[e] See Section 9.1.3.

[f] Secondary emission sources are excess water from dehydration column, vacuum system water, and organics from fractionation column. No data are available on the quantity of these emissions.

Fugitive emissions from pumps and valves may be controlled by an appropriate leak detection system and maintenance program. No control devices are presently being used for secondary emissions.

References for Section 5.24

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2. J. F. Lawson, Emission Control Options for the Synthetic Organic Chemicals Manufacturing Industry: Maleic Anhydride Product Report, EPA Contract No. 68-02-2577, Hydroscience, Inc., Knoxville, TN, March 1978.

7.1 PRIMARY ALUMINUM PRODUCTION

7.1.1 Process Description[1-2]

The base ore for primary aluminum production is bauxite, a hydrated oxide of aluminum consisting off 30 to 70 percent alumina (Al_2O_3) and lesser amounts of iron, silicon and titanium. The bauxite ore is first purified to alumina by the Bayer process, and this is then reduced to elemental aluminum. The production of alumina and the reduction of alumina to aluminum are seldom accomplished at the same location. A schematic diagram of the primary production of aluminum is shown at Figure 7.1-1.

In the Bayer process, the ore is dried, ground in ball mills and mixed with sodium hydroxide to yield aluminum hydroxide. Iron oxide, silica and other impurities are removed by settling, dilution and filtration. Aluminum hydroxide is precipitated from the solution by cooling and is then calcined to produce pure alumina, as in the reaction:

$$\underset{\text{Aluminum hydroxide}}{2Al(OH)_3} \xrightarrow{\text{Heat}} \underset{\text{Water}}{3H_2O} + \underset{\text{Alumina}}{Al_2O_3} \qquad (1)$$

Aluminum metal is manufactured by the Hall-Heroult process, which involves the the electrolytic reduction of alumina dissolved in a molten salt bath of cryolite (Na_3AlF_6) and various salt additives:

$$\underset{\text{Alumina}}{2Al_2O_3} \xrightarrow{\text{Electrolysis}} \underset{\text{Aluminum}}{4Al} + \underset{\text{Oxygen}}{3O_2} \qquad (2)$$

The electrolysis occurs in shallow rectangular cells, or "pots", which are steel shells lined with carbon. Carbon blocks extending into the pot serve as the anodes, and the carbon lining the steel shell acts as the cathode. Cryolite functions as both the electrolyte and the solvent for the alumina. Electrical resistance to the current passing between the electrodes generates heat that maintains cell operating temperatures between 950° and 1000°C (1730° and 1830°F). Aluminum is deposited at the cathode, where it remains as molten metal below the surface of the cryolite bath. The carbon anodes are continuously depleted by the reaction of oxygen (formed during the reaction) and anode carbon, to produce carbon monoxide and carbon dioxide. Carbon consumption and other raw material and energy requirements for aluminum production are summarized in Table 7.1-1. The aluminum product is periodically tapped beneath the cryolite cover and is fluxed to remove trace impurities.

Aluminum reduction cells are distinguished by the anode configuration used in the pots. Three types of pots are currently used, prebaked (PB), horizontal stud Soderberg (HSS), and vertical stud Soderberg (VSS). Most of the aluminum produced in the U. S. is processed in PB cells. These cells use anodes that are press formed from a carbon paste and baked in a direct fired ring furnace or indirect fired tunnel kiln. Volatile organic vapors from the coke and pitch paste in the anodes are emitted, and most are destroyed in the baking furnace. The baked anodes, typically 14 to 24 per cell, are attached to metal rods and serve as replaceable anodes.

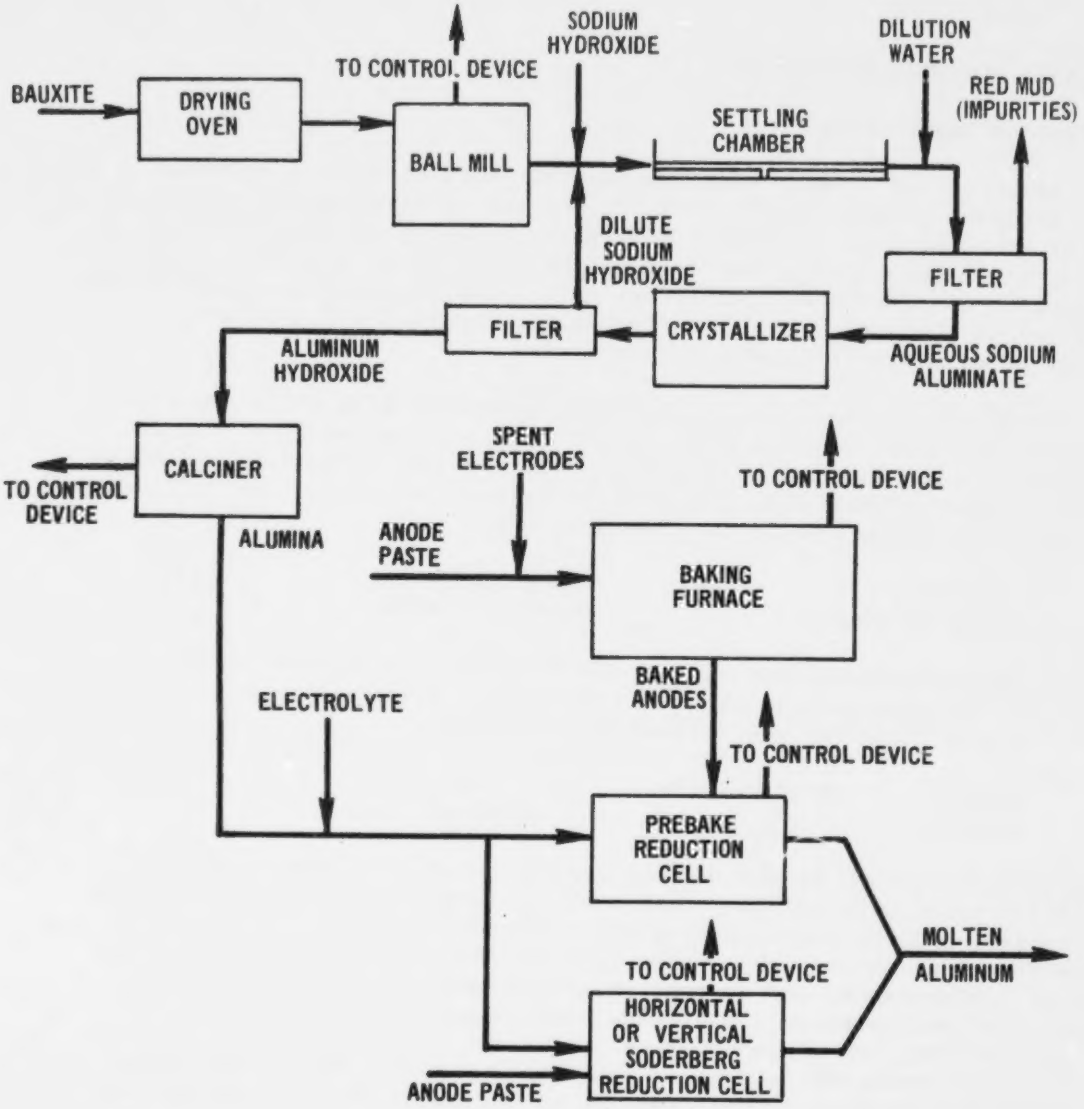

Figure 7.1-1. Schematic diagram of primary aluminum production process.

TABLE 7.1-1. RAW MATERIAL AND ENERGY REQUIREMENTS FOR ALUMINUM PRODUCTION

Parameter	Typical value
Cell operating temperature	950°C (1740°F)
Current through pot line	60,000 - 125,000 amperes
Voltage drop per cell	4.3 - 5.2
Current efficiency	85 - 90%
Energy required	13.2 - 18.7 kwh/kg aluminum (6.0 - 8.5) kwh/lb aluminum)
Weight alumina consumed	1.89 - 1.92 kg(lb) AL_2O_3/kg(lb) aluminum
Weight electrolyte fluoride consumed	0.03 - 0.10 kg(lb) fluoride/kg(lb) aluminum
Weight carbon electrode consumed	0.45 - 0.55 kg(lb) electrode/kg(lb) aluminum

In reduction, the carbon anodes are lowered into the cell and consumed at a rate of about 2.5 cm (1 in.) per day. Prebaked cells are preferred over Soderberg cells for their lower power requirements, reduced generation of volatile pitch vapors from the carbon anodes, and provision for better cell hooding to capture emissions.

The second most commonly used reduction cell is the horizontal stud Soderberg. This type of cell uses a "continuous" carbon anode. A green anode paste of pitch and coke is periodically added at the top of the superstructure and is baked by the heat of the cell to a solid mass as the material moves down the casing. The cell casing consists of aluminum sheeting and perforated steel channels, through which electrode connections or studs are inserted horizontally into the anode paste. During reduction, as the baking anode is lowered, the lower row of studs and the bottom channel are removed, and the flexible electrical connectors are moved to a higher row. Heavy organics from the anode paste are added to the cell emissions. The heavy tars can cause plugging of ducts, fans and emission control equipment.

The vertical stud Soderberg cell is similar to the HSS cell, except that the studs are mounted vertically in the anode paste. Gases from the VSS cells can be ducted to gas burners, and the tar and oils combusted. The construction of the VSS cell prevents the installation of an integral gas collection device, and hooding is restricted to a canopy or skirt at the base of the cell, where the hot anode enters the cell bath.

7.1.2 Emissions and Controls[1-3,9]

Controlled and uncontrolled emission factors for sulfur oxides, fluorides and total particulates are presented in Table 7.1-2. Fugitive particulate and fluoride emission factors for reduction cells are also presented in this Table.

Emissions from aluminum reduction processes consist primarily of gaseous hydrogen fluoride and particulate fluorides, alumina, carbon monoxide, hydrocarbons or organics, and sulfur dioxide from the reduction cells and the anode baking furnaces. Large amounts of particulates are also generated during the calcining of aluminum hydroxide, but the economic value of this dust is such that extensive controls have been employed to reduce emissions to relatively small quantities. Small amounts of particulates are emitted from the bauxite grinding and materials handling processes.

The source of fluoride emissions from reduction cells is the fluoride electrolyte, which contains cryolite, aluminum fluoride (AlF_3), and fluorspar (CaF_2). For normal operation, the weight, or "bath", ratio has the effect of decreasing total fluoride effluents. Cell fluoride emissions are also decreased by lowering the operating temperature and increasing the alumina content in the bath. Specifically, the ratio of gaseous (mainly hydrogen fluoride and silicon tetrafluoride) to particulate fluorides varies from 1.2 to 1.7 with PB and HSS cells, but attains a value of approximately 3.0 with VSS cells.

Particulate emissions from reduction cells consist of alumina and carbon from anode dusting, cryolite, aluminum fluoride, calcium fluoride, chiolite ($Na_5Al_3F_{14}$) and ferric oxide. Representative size distributions for particulate emissions from PB cells and HSS cells are presented in Table 7.1-3. Particulates less than 1 micron in diameter represent the largest fraction (35 - 44 percent) for uncontrolled emissions. Uncontrolled particulate emissions from one HSS cell had a mass mean particle diameter of 5.5 microns. Thirty percent by mass of the particles were submicron, and 16 percent were less than 0.2_μ in diameter.[7]

TABLE 7.1-3. REPRESENTATIVE PARTICLE SIZE DISTRIBUTIONS OF UNCONTROLLED EMISSIONS FROM PREBAKED AND HORIZONTAL STUD SODERBERG CELLS[a]

Size range ($_\mu$)	Particles (wt %)	
	PB	HSS
< 1	35	44
1 to 5	25	26
5 to 10	8	8
10 to 20	5	6
20 to 44	5	4
> 44		

[a] Reference 1.

Emissions from reduction cells also include hydrocarbons or organics, carbon monoxide and sulfur oxides. Small amounts of hydrocarbons are released by PB pots, and larger amounts are emitted from HSS and VSS pots. In vertical cells, these organics are incinerated in integral gas burners. Sulfur oxides originate from sulfur in the anode coke and pitch. The concentrations of sulfur oxides in VSS cell emissions range from 200 to 300 ppm. Emissions from PB plants usually have SO_2 concentrations ranging from 20 to 30 ppm.

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TABLE 7.1-2. EMISSION FACTORS FOR PRIMARY ALUMINUM PRODUCTION PROCESSES[a]

EMISSION FACTOR RATING: A

Operation	Total Particulate[b]		Gaseous Fluoride (HF)		Particulate Fluoride (F)		Sulfur Oxides		References
	Kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	
Bauxite grinding									
Uncontrolled	3.0	6.0	Neg	Neg	NA	NA	NA	NA	1,3
Spray tower	0.9	1.8	Neg	Neg	NA	NA	NA	NA	1,3
Floating bed scrubber	0.85	1.7	Neg	Neg	NA	NA	NA	NA	1,3
Quench tower and spray screen	0.5	1.0	Neg	Neg	NA	NA	NA	NA	1,3
Electrostatic precipitator (ESP)	0.06	0.12	Neg	Neg	NA	NA	NA	NA	1,3
Aluminum hydroxide Calcining									
Uncontrolled	100.0	200.0	Neg	Neg	NA	NA	NA	NA	1,3
Spray tower	30.0	60.0	Neg	Neg	NA	NA	NA	NA	1,3
Floating bed scrubber	28.0	56.0	Neg	Neg	NA	NA	NA	NA	1,3
Quench tower	17.0	34.0	Neg	Neg	NA	NA	NA	NA	1,3
ESP	2.0	4.0	Neg	Neg	NA	NA	NA	NA	1,3
Anode baking furnace									
Uncontrolled	1.5	3.0	0.45	0.9	0.05	0.1	c	c	2,9,10
Fugitive	NA	NA	NA	NA	NA	NA	NA	NA	
Spray tower	0.375	0.75	0.02	0.04	0.015	0.03	NA	NA	9
ESP	0.375	0.75	0.02	0.04	0.015	0.03	NA	NA	2
Dry alumina scrubber	0.03	0.06	0.0045	0.009	0.001	0.002	NA	NA	2,9
Prebake cell									
Uncontrolled	47.0	94.0	12.0	24.0	10.0	20.0	c	c	1,2,9,10
Fugitive	2.5	5.0	0.6	1.2	0.5	1.0	NA	NA	2,9
Emissions to collector	44.5	89.0	11.4	22.8	9.5	19.0	NA	NA	2
Multiple cyclones	9.8	19.6	11.4	22.8	2.1	4.2	NA	NA	2
Dry alumina scrubber	0.9	1.8	0.1	0.2	0.2	0.4	NA	NA	2,9
Dry ESP + spray tower	2.25	4.5	0.7	1.4	1.7	3.4	NA	NA	2,9
Spray tower	8.9	17.8	0.7	1.4	1.9	3.8	NA	NA	2
Floating bed scrubber	8.9	17.8	0.25	0.5	1.9	3.8	NA	NA	2
Coated bag filter dry scrubber	0.9	1.8	1.7	3.4	0.2	0.4	NA	NA	2
Cross flow packed bed	13.15	26.3	3.25	6.7	2.8	5.6	NA	NA	9
Dry + second scrubber	0.35	0.7	0.2	0.4	0.15	0.3	NA	NA	9

TABLE 7.1-2 (CONT.). EMISSION FACTORS FOR PRIMARY ALUMINUM PRODUCTION PROCESSES[a]

EMISSION FACTOR RATING: A

Operation	Total Particulate[b]		Gaseous Fluoride (HF)		Particulate Fluoride (F)		Sulfur Oxides		References
	Kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	
Vertical Soderberg stud cell									
Uncontrolled	39.0	78.0	16.5	33.0	5.5	11.0	NA	NA	2,9
Fugitive	6.0	12.0	2.45	4.9	0.85	1.7	NA	NA	9
Emissions to collector	33.0	66.0	14.05	28.1	4.65	9.3	NA	NA	9
Spray tower	8.25	16.5	0.15	0.3	1.15	2.3	NA	NA	2
Venturi scrubber	1.3	2.6	0.15	0.3	0.2	0.4	NA	NA	2
Multiple cyclones	16.5	33.0	14.05	28.1	2.35	4.7	NA	NA	2
Dry alumina scrubber	0.65	1.3	0.15	0.3	0.1	0.2	NA	NA	2
Scrubber + ESP + spray screen + scrubber	3.85	7.7	0.75	1.5	0.65	1.3	NA	NA	
Horizontal Soderberg stud cell									
Uncontrolled	49.0	98.0	11.0	22.0	6.0	12.0	NA	NA	2,9
Fugitive	5.0	10.0	1.1	2.2	0.6	1.2	NA	NA	2,9
Emissions to collector	44.0	88.0	9.9	19.8	5.4	10.8	NA	NA	2,9
Spray tower	11.0	22.0	3.75	7.5	1.35	2.7	NA	NA	2,9
Floating bed scrubber	9.7	19.4	0.2	0.4	1.2	2.4	NA	NA	2
Scrubber + wet ESP	0.9	1.8	0.1	0.2	0.1	0.2	NA	NA	2,9
Web ESP	0.9	1.8	0.5	1.0	0.1	0.2	NA	NA	9
Dry alumina scrubber	0.9	1.8	0.2	0.4	0.1	0.2	NA	NA	9

[a] For bauxite grinding, expressed as kg/Mg (lb/ton) of bauxite processed. For calcining of aluminum hydroxide, expressed as kg/Mg (lb/ton) of alumina produced. All other factors are per Mg (ton) of molten aluminum product. Emission factors for sulfur oxides have C ratings. NA = not available.

[b] Includes particulate fluorides.

[c] Anode baking furnace, uncontrolled SO_2 emissions (excluding furnace fuel combustion emissions):

20(C)(S)(1-.01 K) kg/Mg [40(C)(S)(1-.01 K) lb/ton]

Prebake (reduction) cell, uncontrolled SO_2 emissions:

0.2(C)(S)(K) kg/Mg [0.4(C)(S)(K) lb/ton]

Where: C = Anode consumption* during electrolysis, lb anode consumed/lb Al produced
S = % sulfur in anode before baking
K = % of total SO_2 emitted by prebake (reduction) cells

*Anode consumption weight is weight of anode paste (coke + pitch) before baking.

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Emissions from anode bake ovens include the products of fuel combustion; high boiling organics from the cracking, distillation and oxidation of paste binder pitch; sulfur dioxide from the carbon paste; fluorides from recycled anode butts; and other particulate matter. The concentrations of uncontrolled SO_2 emissions from anode baking furnaces range from 5 to 47 ppm (based on 3 percent sulfur in coke.)[8]

Casting emissions are mainly fumes of aluminum chloride, which may hydrolyze to HCl and Al_2O_3.

A variety of control devices has been used to abate emissions from reduction cells and anode baking furnaces. To control gaseous and particulate fluorides and particulate emissions, one or more types of wet scrubbers (spray tower and chambers, quench towers, floating beds, packed beds, venturis, and self induced sprays) have been applied to all three types of reduction cells and to anode baking furnaces. Also, particulate control methods such as electrostatic precipitators (wet and dry), multiple cyclones and dry alumina scrubbers (fluid bed, injected, and coated filter types) have been employed with baking furnaces and on all three cell types. Also, the alumina adsorption systems are being used on all three cell types to control both gaseous and particulate fluorides by passing the pot offgases through the entering alumina feed, on which the fluorides are absored. This technique has an overall control efficiency of 98 to 99 percent. Baghouses are then used to collect residual fluorides entrained in the alumina and to recycle them to the reduction cells. Wet electrostatic precipitators approach adsorption in particulate removal efficiency but must be coupled to a wet scrubber or coated baghouse to catch hydrogen fluoride.

Scrubber systems also remove a portion of the SO_2 emissions. These emissions could be reduced by wet scrubbing or by reducing the quantity of sulfur in the anode coke and pitch, i. e., calcinating the coke.

In the aluminum hydroxide calcining, bauxite grinding and materials handling operations, various dry dust collection devices (centrifugal collectors, multiple cyclones, or electrostatic precipitators and/or wet scrubbers) have been used.

Potential sources of fugitive particulate emissions in the primary aluminum industry are bauxite grinding, materials handling, anode baking and three types of reduction cells (see Table 7.1-2). These fugitives probably have particle size distributions similar to those presented in Table 7.1-3.

References for Section 7.1

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2. Air Pollution Control in the Primary Aluminum Industry, Volume I, EPA-450/3-73-004a, U. S. Environmental Protection Agency, Research Triangle Park, NC, July 1973.

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4. Emissions from Wet Scrubbing System, Report Number Y-7730-E, York Research Corp., Stamford, CT, May 1972.

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9. Primary Aluminum: Guidelines for Control of Fluoride Emissions from Existing Primary Aluminum Plants, EPA-450/2-78-049b, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1979.

10. Written communication from T. F. Albee, Reynolds Aluminum, Richmond, VA, to A. A. MacQueen, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 20, 1982.

7.5 IRON AND STEEL PRODUCTION

7.5.1 Process Description and Emissions[1-2]

Iron and steel manufacturing may be grouped into eight generic process operations: 1) coke production, 2) sinter production, 3) iron production, 4) steel production, 5) semifinished product preparation, 6) finished product preparation, 7) heat and electricity supply and 8) handling and transport of raw, intermediate and waste materials. Figure 7.5-1, a general flow diagram of the iron and steel industry, interrelates these categories. Coke production is discussed in detail in Section 7.2 of this publication, and more information on the handling and transport of materials is found in Chapter 11.

Sinter Production - The sintering process converts fine raw materials like fine iron ore, coke breeze, fluxstone, mill scale and flue dust into an agglomerated product of suitable size for charging into a blast furnace. The materials are mixed with water to provide cohesion in a mixing mill and are placed on a continuous moving grate called the sinter strand. A burner hood above the front third of the sinter strand ignites the coke in the mixture. Once ignited, combustion is self supporting and provides sufficient heat, 1300 to 1480°C (2400 to 2700°F), to cause surface melting and agglomeration of the mix. On the underside of the sinter machine lie windboxes that draw the combusted air through the material bed into a common duct to a particulate control device. The fused sinter is discharged at the end of the sinter machine, where it is crushed and screened, and any undersize portion is recycled to the mixing mill. The remaining sinter is cooled in open air by water spray or by mechanical fan to draw off the heat from the sinter. The cooled sinter is screened a final time, with the fines being recycled and the rest being sent to charge the blast furnaces.

Emissions occur at several points in the sintering process. Points of particulate generation are the windbox, the discharge (sinter crusher and hot screen), the cooler and the cold screen. In addition, inplant transfer stations generate emissions which can be controlled by local enclosures. All the above sources except the cooler normally are vented to one or two control systems.

Iron Production - Iron is produced in blast furnaces, which are large refractory lined chambers into which iron (as natural ore or as agglomerated products such as pellets or sinter, coke and limestone) is charged and allowed to react with large amounts of hot air to produce molten iron. Slag and blast furnace gases are byproducts of this operation. The average charge to produce one unit weight of iron requires 1.7 unit weights of iron bearing charge, 0.55 unit weights of coke, 0.2 unit weights of limestone, and 1.9 unit weights of air. Average blast furnace byproducts consist of 0.3 unit weights of slag, 0.05 unit weights of flue dust, and 3.0 unit weights of gas per unit of iron produced. The flue dust and other iron ore fines from the process are converted into useful blast furnace charge by the sintering operation.

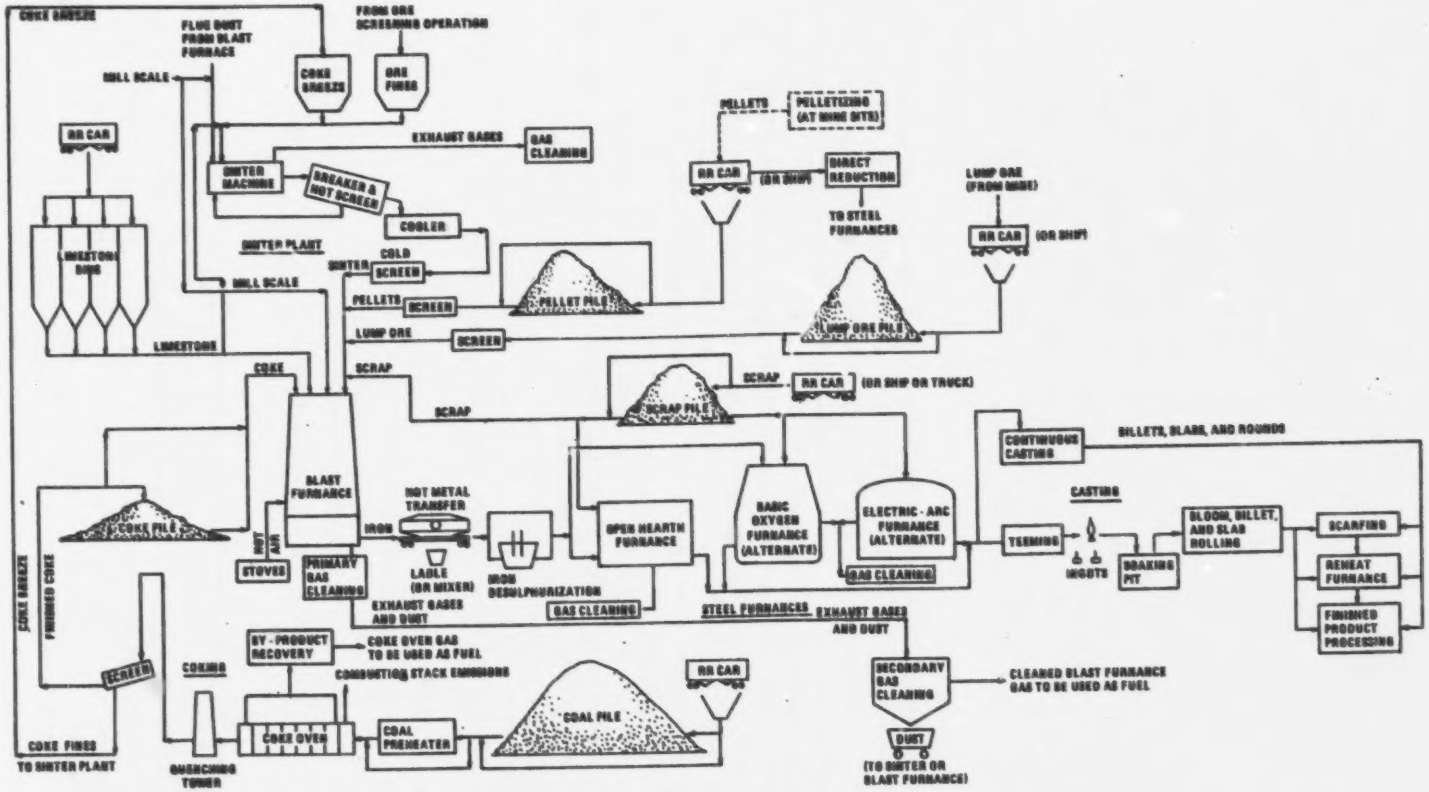

Figure 7.5-1. General flow diagram for the iron and steel industry.

Because of its high carbon monoxide content, this blast furnace gas has a low heating value, about 2790 to 3350 joules per cubic liter (75 to 90 BTU/ft^3) and is used as a fuel within the steel plant. Before it can be efficiently oxidized, however, the gas must be cleaned of particulate. Initially, the gases pass through a settling chamber or dry cyclone to remove about 60 percent of the particulate. Next, the gases undergo a one or two stage cleaning operation. The primary cleaner is normally a wet scrubber, which removes about 90 percent of the remaining particulate. The secondary cleaner is a high energy wet scrubber (usually a venturi) or an electrostatic precipitator, either of which can remove up to 90 percent of the particulate that eludes the primary cleaner. Together these control devices provide a clean fuel of less than 0.05 grams per cubic meter (0.02 gr/ft^3) for use in the steel plant.

Emissions occur during the production of iron when there is a blast furnace "slip" and during hot metal transfer operations in the cast house. All gas generated in the blast furnace is normally cleaned and used for fuel. Conditions such as "slips", however, can cause instant emissions of carbon monoxide and particulates. Slips occur when a stratum of the material charged to a blast furnace does not settle with the material below it, thus leaving a gas filled space between the two portions of the charge. When this unsettled stratum of charge collapses, the displaced gas may cause the top gas pressure to increase above the safety limit, thus opening a counter weighted bleeder valve to the atmosphere.

Steel Production (Basic Oxygen Furnace) - The basic oxygen process is used to produce steel from a furnace charge typically composed of 70 percent molten blast furnace metal and 30 percent scrap metal by use of a stream of commercially pure oxygen to oxidize the impurities, principally carbon and silicon. Most of the basic oxygen furnaces (BOF) in the United States have oxygen blown through a lance in the top of the furnace. However, the Quelle Basic Oxygen Process (QBOP), which is growing in use, has oxygen blown through tuyeres in the bottom of the furnace. Cycle times for the basic oxygen process range from 25 to 45 minutes.

The large quantities of carbon monoxide (CO) produced by the reactions in the BOF can be combusted at the mouth of the furnace and then vented to gas cleaning devices, as with open hoods, or the combustion can be suppressed at the furnace mouth, as with closed hoods. The term "closed hood" is actually a misnomer, since the opening at the furnace mouth is large enough to allow approximately 10 percent of theoretical air to enter. Although most furnaces installed before 1975 are of the open hood design, nearly all the QBOPs in the United States have closed hoods, and most of the new top blown furnaces are being designed with closed hoods.

There are several sources of emissions in the basic oxygen furnace steel making process, 1) the furnace mouth during refining - with collection by local full (open) or suppressed (closed) combustion hoods, 2) hot metal transfer to charging ladle, 3) charging scrap and hot metal, 4) dumping slag and 5) tapping steel.

Steel Production (Electric Arc Furnaces) - Electric arc furnaces (EAF) are used to produce carbon and alloy steels. The charge to an EAF is nearly always 100 percent scrap. Direct arc electrodes through the roof of the furnace melt the scrap. An oxygen lance may or may not be used to speed the melting and refining process. Cycles range from 1-1/2 to 5 hours for carbon steel and from 5 to 10 hours for alloy steel.

Sources of emissions in the electric arc furnace steel making process are 1) emissions from melting and refining, often vented through a hole in the furnace roof, 2) charging scrap, 3) dumping slag and 4) tapping steel. In interpreting and using emission factors for EAFs, it is important to know what configuration one is dealing with. For example, if an EAF has a building evacuation system, the emission factor before the control device would represent all melting, refining, charging, tapping and slagging emissions which ascend to the building roof. Reference 2 has more details on various configurations used to control electric arc furnaces.

Steel Production (Open Hearth Furnaces) - In the open hearth furnace (OHF), a mixture of iron and steel scrap and hot metal (molten iron) is melted in a shallow rectangular basin or "hearth". Burners producing a flame above the charge provide the heat necessary for melting. The mixture of scrap and hot metal can vary from all scrap to all hot metal, but a half and half mixture is a reasonable industry average. The process may or may not be oxygen lanced, with process cycle times approximately 8 hours and 10 hours, respectively.

Sources of emissions in the open hearth furnace steel making process are 1) transferring hot metal, 2) melting and refining the heat, 3) charging of scrap and/or hot metal, 4) dumping slag and 5) tapping steel.

Semifinished Product Preparation - After the steel has been tapped, the molten metal is teemed into ingots which are later heated to form blooms, billets or slabs. (In a continuous casting operation, the molten metal may bypass this entire process.) The product next goes through a process of surface preparation of semifinished steel (scarfing). A scarfing machine removes surface defects before shaping or rolling of the steel billets, blooms and slabs by applying jets of oxygen to the surface of the steel, which is at orange heat, thus removing a thin layer of the metal by rapid oxidation. Scarfing can be performed by machine on hot semifinished steel or by hand on cold or slightly heated semifinished steel. Emissions occur during teeming as the molten metal is poured, and when the semifinished steel products are manually or machine scarfed to remove surface defects.

Miscellaneous Combustion Sources - Iron and steel plants require energy (heat or electricity) for every plant operation. Some energy operations on plant property that produce emissions are boilers, soaking pits and slab furnaces which burn coal, No. 2 fuel oil, natural gas, coke oven gas or blast furnace gas. In soaking pits, ingots are heated until the temperature distribution over the cross section of the ingots is acceptable and the surface temperature is uniform for further rolling into semifinished products (blooms, billets and slabs). In slab furnaces, a slab is heated before being rolled into finished products (plates, sheets or strips). The emissions from the combustion of natural gas, fuel oil or coal for boilers can be found in Chapter 1 of this document. Estimated emissions from these same fuels used in soaking pits or slab furnaces can be the same as those for boilers, but since it is estimation, the factor rating drops to D.

Emission factor data for blast furnace gas and coke oven gas are not available and must be estimated. There are three facts available for making the estimation. First, the gas exiting the blast furnace passes through primary and secondary cleaners and can be cleaned to less than 0.05 grams per cubic meter (0.02 gr/ft^3). Second, nearly one third of the coke oven gas is methane. Third, there are no blast furnace gas constituents that generate particulate when burned. The combustible constituent of blast furnace gas is CO, which burns clean. Based on facts one and three, the emission factor for combustion of blast furnace gas is equal to the particulate loading of that fuel, 0.05 grams per cubic meter (2.9 lb/10^6 ft^3).

Emissions for combustion of coke oven gas can be estimated in the same fashion. Assume that cleaned coke oven gas has as much particulate as cleaned blast furnace gas. Since one third of the coke oven gas is methane, the main component of natural gas, it is assumed that the combustion of this methane in coke oven gas generates 0.06 grams per cubic meter (3.3 lb/10^6 ft^3) of particulate. Thus, the emission factor for the combustion of coke oven gas is the sum of the particulate loading and that generated by the methane combustion, or 0.1 grams per cubic meter (6.2 lb/10^6 ft^3).

Open Dust Sources - Like process emission sources, open dust sources contribute to the atmospheric particulate burden. Open dust sources include 1) vehicle traffic on paved and unpaved roads, 2) raw material handling outside of buildings and 3) wind erosion from storage piles and exposed terrain. Vehicle traffic consists of plant personnel and visitor vehicles; plant service vehicles; and trucks handling raw materials, plant deliverables, steel products and waste materials. Raw materials are handled by clamshell buckets, bucket/ladder conveyors, rotary railroad dumps, bottom railroad dumps, front end loaders, truck dumps, and conveyor transfer stations, all of which disturb the raw material and expose fines to the wind. Even fine materials resting on flat areas or in storage piles are exposed and are subject to wind erosion. It is not unusual to have several million tons of raw materials stored at a plant and to have in the range of 10 to 100 acres of exposed area there.

Open dust source emission factors for iron and steel production are presented in Table 7.5-1. These factors were determined through source testing at various integrated iron and steel plants.

As an alternative to the single valued open dust emission factors given in Table 7.5-1, empirically derived emission factor equations are presented in Chapter 11 of this document. Each equation was developed for a source operation defined on the basis of a single dust generating mechanism which crosses industry lines, such as vehicle traffic on unpaved roads. The predictive equation explains much of the observed variance in measured emission factors by relating emissions to parameters which characterize source conditions. These parameters may be grouped into three categories: 1) measures of source activity or energy expended (e.g., the speed

TABLE 7.5-1. UNCONTROLLED PARTICULATE EMISSION FACTORS FOR OPEN DUST SOURCES AT IRON AND STEEL MILLS[a]

Operation	Emissions by particle size range (aerodynamic diameter)					Units[b]	Emission Factor Rating
	< 30 μm	< 15 μm	< 10 μm	< 5 μm	< 2.5 μm		
Continuous drop							
Conveyor transfer station							
Sinter[c]	13	9.0	6.5	4.2	2.3	g/Mg	D
	0.026	0.018	0.013	0.0084	0.0046	lb/T	D
Pile formation - stacker							
Pellet ore[c]	1.2	0.75	0.55	0.32	0.17	g/Mg	B
	0.0024	0.0015	0.0011	0.00064	0.00034	lb/T	B
Lump ore[c]	0.15	0.095	0.075	0.040	0.022	g/Mg	C
	0.00030	0.00019	0.00015	0.000081	0.000043	lb/T	C
Coal[d]	0.055	0.034	0.026	0.014	0.0075	g/Mg	E
	0.00011	0.000069	0.000052	0.000029	0.000015	lb/T	E
Batch drop							
Front end loader/truck[c]							
High silt slag	13	8.5	6.5	4.0	2.3	g/Mg	C
	0.026	0.017	0.013	0.0080	0.0046	lb/T	C
Low silt slag	4.4	2.9	2.2	1.4	0.80	g/Mg	C
	0.0088	0.0058	0.0043	0.0028	0.0016	lb/T	C
Vehicle travel on unpaved roads							
Light duty vehicle[d]	0.51	0.37	0.28	0.18	0.10	kg/VKT	C
	1.8	1.3	1.0	0.64	0.37	lb/VMT	C
Medium duty vehicle[d]	2.1	1.5	1.2	0.70	0.42	kg/VKT	C
	7.3	5.2	4.1	2.5	1.5	lb/VMT	C
Heavy duty vehicle[b]	3.9	2.7	2.1	1.4	0.76	kg/VKT	B
	14	9.7	7.6	4.8	2.7	lb/VMT	B
Vehicle travel on paved roads							
Light/heavy vehicle mix[c]	0.22	0.16	0.12	0.079	0.042	kg/VKT	C
	0.78	0.56	0.44	0.28	0.15	lb/VMT	C

[a] Predictive emission factor equations, which generally provide more accurate estimates of emissions, are presented in Chapter 11.
[b] Units/unit of material transferred. Units/unit of distance traveled.
[c] Reference 3. Interpolation to other particle sizes will be approximate.
[d] Reference 4. Interpolation to other particle sizes will be approximate.

and weight of a vehicle traveling on an unpaved road), 2) properties of the material being disturbed (e.g., the content of suspendible fines in the surface material on an unpaved road) and 3) climatic parameters (e.g., number of precipitation free days per year, when emissions tend to a maximum).

Because the predictive equations allow for emission factor adjustment to specific source conditions, the equations should be used in place of the factors in Table 7.5-1, if emission estimates for sources in a specific iron and steel facility are needed. However, the generally higher quality ratings assigned to the equations are applicable only if 1) reliable values of correction parameters have been determined for the specific sources of interest and 2) the correction parameter values lie within the ranges tested in developing the equations. Chapter 11 lists measured properties of aggregate process materials and road surface materials in the iron and steel industry, which can be used to estimate correction parameter values for the predictive emission factor equations, in the event that site specific values are not available. Use of mean correction parameter values from Chapter 11 reduces the quality ratings of the emission factor equation by one level.

Particulate emission factors for iron and steel plant processes are in Table 7.5-2. These emission factors are a result of an extensive investigation by EPA and the American Iron and Steel Institute.[2] Carbon monoxide emission factors are in Table 7.5-3.[5]

TABLE 7.5-2. PARTICULATE EMISSION FACTORS FOR IRON AND STEEL MILLS[a]

Source	Units	Emissions	Emission Factor Rating
Blast furnaces			
Slips	kg (lb)/slip	39.5 (87)	D
Uncontrolled cast house emissions	kg/Mg (lb/ton) hot metal		
Monitor		0.3 (0.6)	B
Tap hole and trough (not runners)		0.15 (0.3)	B
Sintering			
Windbox emissions	kg/Mg (lb/ton) finished sinter		
Uncontrolled			
Leaving grate		5.56 (11.1)	B
After coarse particulate removal		4.35 (8.7)	A
Controlled by dry ESP		0.8 (1.6)	B
Controlled by wet ESP		0.085 (0.17)	B
Controlled by scrubber		0.235 (0.47)	B
Controlled by cyclone		0.5 (1)	B
Sinter discharge (breaker and hot screens)	kg/Mg (lb/ton) finished sinter		
Uncontrolled		3.4 (6.8)	B
Controlled by baghouse		0.05 (0.1)	B
Controlled by orifice scrubber		0.295 (0.59)	A
Windbox and discharge	kg/Mg (lb/ton) finished sinter		
Controlled by baghouse		0.15 (0.3)	A
Basic oxygen furnaces			
Top blown furnace melting and refining	kg/Mg (lb/ton) steel		
Uncontrolled		14.25 (28.5)	B
Controlled by open hood vented to:			
ESP		0.065 (0.13)	A
Scrubber		0.045 (0.09)	B
Controlled by closed hood vented to:			
Scrubber		0.0034 (0.0068)	A
QBOP melting and refining	kg/Mg (lb/ton) steel		
Controlled by scrubber		0.028 (0.056)	A
Charging	kg/Mg (lb/ton) hot metal		
At source		0.3 (0.6)	A
At building monitor		0.071 (0.142)	B
Tapping	kg/Mg (lb/ton) steel		
At source		0.46 (0.92)	A
At building monitor		0.145 (0.29)	B
Hot metal transfer	kg/Mg (lb/ton) hot metal		
At source		0.095 (0.19)	A
At building monitor		0.028 (0.056)	B
BOF monitor (all sources)	kg/Mg (lb/ton) steel	0.25 (0.5)	B
Electric arc furnaces			
Melting and refining	kg/Mg (lb/ton) steel		
Uncontrolled			
Carbon steel		19 (38)	C
Charging, tapping and slagging	kg/Mg (lb/ton) steel		
Uncontrolled emissions escaping monitor		0.7 (1.4)	C
Melting, refining, charging, tapping and slagging	kg/Mg (lb/ton) steel		
Uncontrolled			
Alloy steel		5.65 (11.3)	A
Carbon steel		25 (50)	C
Controlled by:			
Configuration 1 (building evacuation to baghouse for alloy steel)		0.15 (0.3)	A
Configuration 2 (DSE plus charging hood vented to common baghouse for carbon steel)		0.0215 (0.043)	C

(continued)

TABLE 7.5-2. PARTICULATE EMISSION FACTORS FOR IRON AND STEEL MILLS[a] (continued)

Source	Units	Emissions	Emission Factor Rating
Open hearth furnaces			
Melting and refining	kg/Mg (lb/ton) steel		
Uncontrolled		10.55 (21.1)	A
Controlled by ESP		0.14 (0.28)	A
Roof monitor emissions		0.084 (0.168)	C
Teeming			
Leaded steel	kg/Mg (lb/ton) steel		
Uncontrolled (as measured at the source)		0.405 (0.81)	A
Controlled by side draft hood vented to baghouse		0.0019 (0.0038)	A
Unleaded steel			
Uncontrolled (as measured at the source)		0.035 (0.07)	A
Controlled by side draft hood vented to baghouse		0.0008 (0.0016)	A
Machine scarfing			
Uncontrolled	kg/Mg (lb/ton) metal through scarfer	0.05 (0.1)	B
Controlled by ESP		0.0115 (0.023)	A
Miscellaneous combustion sources[b]			
Boilers, soaking pits and slab reheat furnaces	$kg/10^9$ J ($lb/10^6$ BTU)		
Blast furnace gas		0.015 (0.035)	D
Coke oven gas		0.0052 (0.012)	D

[a] Reference 2. ESP = electrostatic precipitator. DSE = direct shell evacuation.

[b] For fuels such as coal, fuel oil and natural gas, use the emission factors presented in Chapter 1 of this document. The factor rating for these fuels in boilers is A, and in soaking pits and slab reheat furnaces is D.

TABLE 7.5-3. UNCONTROLLED CARBON MONOXIDE EMISSION FACTORS FOR IRON AND STEEL MILLS[a]

EMISSION FACTOR RATING: C

Source	kg/Mg	lb/ton
Sintering windbox[b]	22	44
Basic oxygen furnace	69	138
Electric arc furnace	9	18

[a] Reference 5.

[b] Expressed as units of emissions per unit of finished sinter.

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8.14 GYPSUM MANUFACTURING

8.14.1 Process Description[1-2]

Gypsum is calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), a white or gray naturally occurring mineral. Raw gypsum ore is processed into a variety of products such as a Portland cement additive, soil conditioner, industrial and building plasters, and gypsum wallboard. To produce plasters or wallboard, gypsum must first be partially dehydrated or calcined to produce calcium sulfate hemihydrate ($CaSO_4 \cdot \frac{1}{2}H_2O$), commonly called stucco.

A flow diagram for a typical gypsum process producing both crude and finished gypsum products is shown in Figure 8.14-1. In this process, gypsum is crushed, dried, ground and calcined. Some of the operations shown in Figure 8.14-1 are not performed at all gypsum plants. Some plants produce only wallboard, and many plants do not produce soil conditioner.

Gypsum ore, from quarries and/or underground mines, is crushed and stockpiled near a plant. As needed, the stockpiled ore is further crushed and screened to about 50 millimeters (2 inches) in diameter. If the moisture content of the mined ore is greater than about 0.5 weight percent, the ore must be dried in a rotary dryer or a heated roller mill. Ore dried in a rotary dryer is conveyed to a roller mill where it is ground to 90 percent less 149 micrometers (100 mesh). The ground gypsum exits the mill in a gas stream and is collected in a product cyclone. Ore is sometimes dried in the roller mill by heating the gas stream, so that drying and grinding are accomplished simultaneously and no rotary dryer is needed. The finely ground gypsum ore is known as landplaster, which may be used as soil conditioner.

In most plants, landplaster is fed to kettle calciners or flash calciners, where it is heated to remove three quarters of the chemically bound water to form stucco. Calcination occurs at approximately 120 to 150°C (250 to 300°F), and 0.908 megagrams (Mg) (one ton) of gypsum calcines to about 0.77 Mg (0.85 ton) of stucco.

In kettle calciners, the gypsum is indirectly heated by hot combustion gas passed through flues in the kettle, and the stucco product is discharged into a "hot pit" located below the kettle. Kettle calciners may be operated in either batch or continuous modes. In flash calciners, the gypsum is directly contacted with hot gases, and the stucco product is collected at the bottom of the calciner. A major gypsum manufacturer holds a patent on the design of the flash calciner.

At some gypsum plants, drying, grinding and calcining are performed in heated impact mills. In these mills, hot gas contacts gypsum as it is ground. The gas dries and calcines the ore and then conveys the stucco to a product cyclone for collection. The use of heated impact mills eliminates the need for rotary dryers, calciners and roller mills.

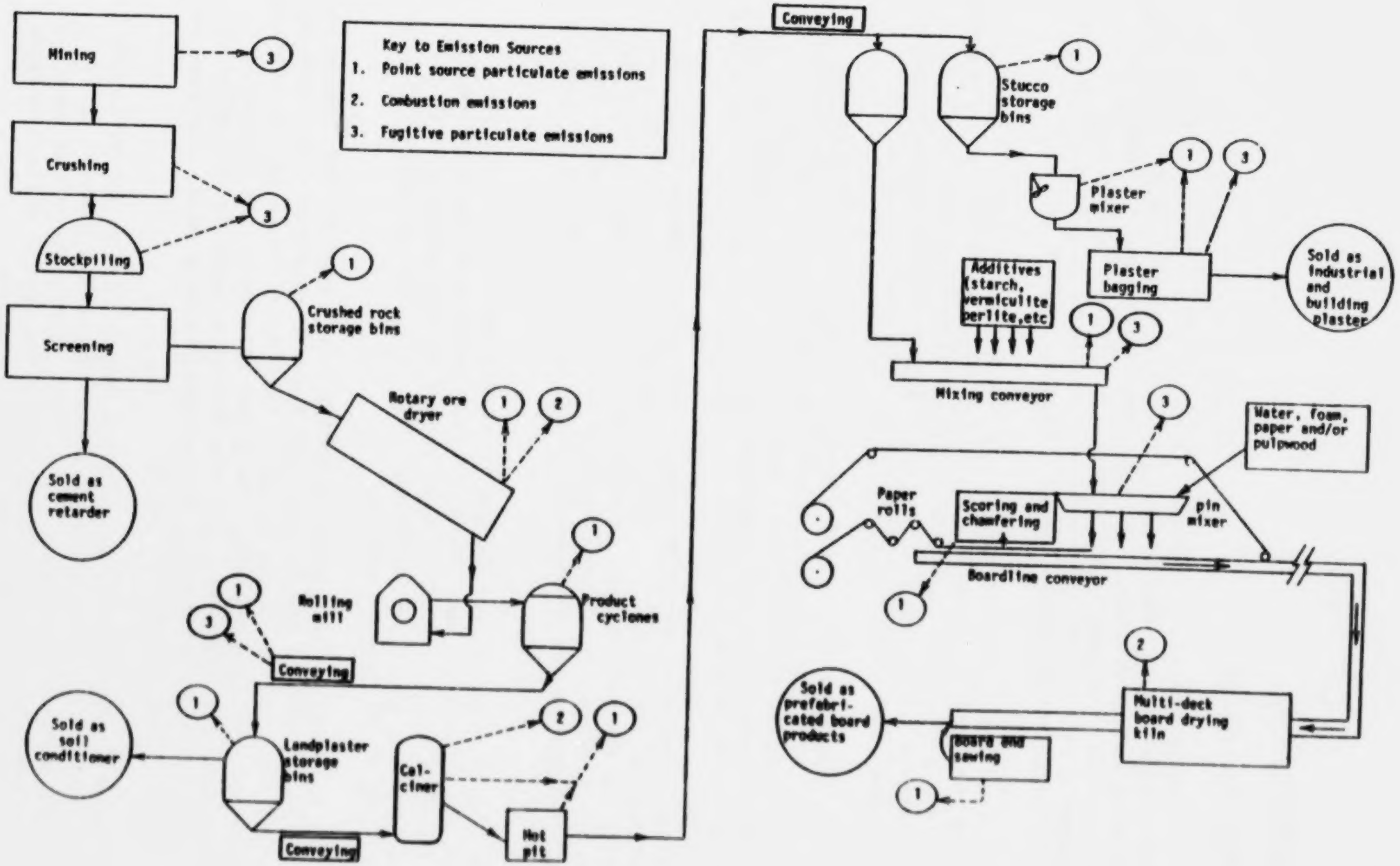

Figure 8.14-1. Overall gypsum manufacturing process flow diagram.

Gypsum and stucco usually are transferred from one process to another in screw conveyors or bucket elevators. Storage bins or silos are normally located downstream of roller mills and calciners but may also be used elsewhere.

In the manufacture of plasters, stucco is ground further in a tube or ball mill and then batch mixed with retarders and stabilizers to produce plasters with specific setting rates. The thoroughly mixed plaster is fed continuously from intermediate storage bins to a bagging operation.

In the manufacture of wallboard, stucco from storage is first mixed with dry additives such as perlite, starch, fiberglass or vermiculite. This dry mix is combined with water, soap foam, accelerators and shredded paper or pulpwood in a pin mixer at the head of a board forming line. The slurry is then spread between two paper sheets that serve as a mold. The edges of the paper are scored, and sometimes chamfered, to allow precise folding of the paper to form the edges of the board. As the wet board travels the length of a conveying line, the calcium sulfate hemihydrate combines with the water in the slurry to form solid calcium sulfate dihydrate or gypsum, resulting in rigid board. The board is rough cut to length, and it enters a multideck kiln dryer where it is dried by direct contact with hot combustion gases or by indirect steam heating. The dried board is conveyed to the board end sawing area and is trimmed and bundled for shipment.

8.14.2 Emissions and Controls[2]

Potential emission sources in gypsum manufacturing plants are shown in Figure 8.14-1. Although several sources may emit gaseous pollutants, particulate emissions are of greatest concern. The major sources of particulate emissions include rotary ore dryers, grinding mills, calciners and board end sawing operations. Particulate emission factors for these operations are shown in Table 8.14-1. All these factors are based on output production rates. Particle size data for ore dryers, calciners and board end sawing operations are shown in Tables 8.14-2 and 8.14-3.

The uncontrolled emission factors presented in Table 8.14-1 represent the process dust entering the emission control device. It is important to note that emission control devices are frequently needed to collect the product from some gypsum processes and, thus, are commonly thought of by the industry as process equipment and not added control devices.

Emissions sources in gypsum plants are most often controlled with fabric filters. These sources include:

- rotary ore dryers
- roller mills
- impact mills
- kettle calciners
- flash calciners
- board end sawing
- scoring and chamfering
- plaster mixing and bagging
- conveying systems
- storage bins

Uncontrolled emissions from scoring and chamfering, plaster mixing and bagging, conveying systems, and storage bins are not well quantified.

TABLE 8.14-1. PARTICULATE EMISSION FACTORS FOR GYPSUM PROCESSING[a]

EMISSION FACTOR RATING: B

Process	Uncontrolled[b]		With fabric filter[c]		With electrostatic precipitator	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Crushers, screens, stockpiles, roads	d	d	-	-	-	-
Rotary ore dryers[e,f,g]	$0.0042(FFF)^{1.77}$	$0.16(FFF)^{1.77}$	0.02[h]	0.04[h]	NA	
Roller mills[i]	1.3[j]	2.6[j]	0.06	0.12	0.05[k]	0.09[k]
Impact mills[e,l]	50[g,j]	100[g,j]	0.01	0.02	NA	
Flash calciners[e,m]	19	37	0.02	0.04	NA	
Continuous kettle calciners[n]	21[p]	41[p]	0.003[p]	0.006[p]	0.05[j]	0.09[j]
	kg/m^2	$lb/100\ ft^2$	$kg/10^6\ m^2$	$lb/10^6\ ft^2$		
Board end sawing[q]						
2.4 m (8 ft) boards	0.04	0.8	36	7.5		
3.7 m (12 ft) boards	0.03	0.5	36	7.5		

[a] Based on process output production rate. Rating applies to all factors except where otherwise noted. Dash = not applicable. NA = not available.

[b] Factors represent any dust entering the emission control device.

[c] References 3-6, 8-11. Factors for sources controlled with fabric filters are based on pulse jet fabric filters with actual air/cloth ratios ranging from 2.3:1 - 7.0:1, mechanical shaker fabric filters with ratios from 1.5:1 - 4.6:1, and a reverse flow fabric filter with a ratio of 2.3:1.

[d] Factors for these operations are in Sections 8.19 and 11.2.

[e] Includes particulate matter from fuel combustion.

[f] References 3-4, 8, 11-12. Equation is for emission rate upstream of any process cyclones and is applicable only to concurrent rotary ore dryers with flowrates of 7.5 m^3/s (16,000 acfm) or less. FFF in the uncontrolled emission factor equation is "flow feed factor", the ratio of gas mass rate per unit dryer cross sectional area to the dry mass feed rate, in the following units:

$$\frac{kg/hr - m^2 \text{ of gas flow}}{Mg/hr \text{ dry feed}} \quad \text{or} \quad \frac{lb/hr - ft^2 \text{ of gas flow}}{ton/hr \text{ dry feed}}$$

Measured uncontrolled emission factors for 4.2 and 5.7 m^3/s (9000 and 12,000 acfm) range from 5 - 60 kg/Mg (10 - 120 lb/ton).

[g] EMISSION FACTOR RATING: C.

[h] Applicable to rotary dryers with and without process cyclones upstream of the fabric filter.

[i] References 11-14. Factors apply to both heated and unheated roller mills.

[j] Factors represent emissions downstream of the product cyclone.

[k] Factor is for combined emissions from roller mills and kettle calciners, based on the sum of the roller mill and kettle calciner output production rates.

[l] References 9,15. As used here, an impact mill is a process unit with process cyclones and is used to dry, grind and calcine gypsum simultaneously.

[m] References 3, 6, 10. A flash calciner is a process unit used to calcine gypsum through direct contact with hot gas. No grinding is performed in this unit.

[n] References 4-5, 11, 13-14.

[p] Based on emissions from both the kettle and the hot pit. Not applicable to batch kettle calciners.

[q] References 4-5, 16. Based on 13 mm (½ in.) board thickness and 1.2 m (4 ft) board width. For other board thicknesses, multiply the appropriate emission factor by 0.079 times board thickness in millimeters, or by 2 times board thickness in inches.

TABLE 8.14-2. UNCONTROLLED PARTICLE SIZE DATA FOR GYPSUM PROCESSING

Process	Weight Percent	
	10 μm	2 μm
Rotary ore dryer		
with cyclones[a]	45[b]	12[b]
without cyclones[c]	8[b]	1[b]
Continuous kettle calciners[d]	63[e]	17[e]
Flash calciners[f]	38[b]	10[b]

[a] Reference 4.
[b] Aerodynamic diameter, Andersen analysis.
[c] Reference 3.
[d] References 4-5.
[e] Equivalent diameter, Bahco and Sedigraph analyses.
[f] References3, 6.

TABLE 8.14-3. PARTICLE SIZE DATA FOR GYPSUM PROCESSING OPERATIONS CONTROLLED WITH FABRIC FILTERS[a]

Process	Weight Percent	
	10 μm	2 μm
Rotary ore dryer		
with cyclones[b]	c	9
without cyclones[d]	26	9
Flash calciners[e]	84	52
Board end sawing[e]	76	49

[a] Aerodynamic diameters, Andersen analysis.
[b] Reference 4.
[c] Not available
[d] Reference 3.
[e] References 3, 6.
[f] References 4-5.

Emissions from some gypsum sources are also controlled with electrostatic precipitators (ESP). These sources include rotary ore dryers, roller mills, kettle calciners and conveying systems. Although rotary ore dryers may be controlled separately, emissions from roller mills and conveying systems are usually controlled jointly with kettle calciner emissions. Moisture in the kettle calciner exit gas improves the ESP performance by lowering the resistivity of the dust.[7]

Other sources of particulate emissions in gypsum plants are primary and secondary crushers, screens, stockpiles and roads. If quarrying is part of the mining operation, particulate emissions may also result from drilling and blasting. Emission factors for some of these sources are presented in Sections 8.19 and 11.2.

Gaseous emissions from gypsum processes result from fuel combustion and may include nitrogen oxides, carbon monoxide and sulfur oxides. Processes using fuel include rotary ore dryers, heated roller mills, impact mills, calciners and board drying kilns. Although some plants use residual fuel oil, the majority of the industry uses clean fuels such as natural gas or distillate fuel oil.[17] Emissions from fuel combustion may be estimated using emission factors presented in Sections 1.3 and 1.4.

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8.19 CONSTRUCTION AGGREGATE PROCESSING

General[1]

The processing of construction aggregate (crushed stone, sand and gravel, etc.) usually involves a series of distinct yet interdependent operations. These include quarrying or mining operations (drilling, blasting, loading and hauling) and plant process operations (crushing, grinding, conveying and other material handling and transfer operations). Many kinds of construction aggregate require additional processing (washing, drying, etc.) depending on rock type and consumer requirements. Some of the individual operations take place with high moisture, such as wet crushing and grinding, washing, screening and dredging. These wet processes do not generate appreciable particulate emissions. Although such operations may be a severe nuisance problem, with local violations of ambient particulate standards, their generally large particles can usually be controlled quite readily and satisfactorily to prevent such problems.

The construction aggregate industry can be broken into various categories, depending on source, mineral type or form, physical characteristics, wet versus dry, washed or unwashed, and end uses, to name but a few. The industry is categorized here into Section 8.19.1, Sand and Gravel Processing, and Section 8.19.2, Crushed Stone Processing. Sand and gravel generally are mined wet and consist of discrete particles or stones, while crushed stone normally originates from solid strata which are broken by blasting and which will require substantial crushing to be a useful consumer product. Further Sections will be published when data on other processes become available.

Reference for Section 8.19

1. Air Pollution Control Techniques for Nonmetallic Minerals Industry, EPA-450/3-82-014, U. S. Environmental Protection Agency, Research Triangle Park, NC, August 1982.

Notice: Work is being done on emission factors for 8.19.2, Crushed Stone Processing, and these factors will be presented in a future Supplement to AP-42.

This new work will replace the present 8.20, Stone Quarrying and Processing.

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8.19.1 SAND AND GRAVEL PROCESSING

8.19.1.1 Process Description[1-2]

Deposits of sand and gravel, the consolidated granular materials resulting from the natural disintegration of rock or stone, are generally found in banks and pits and in subterranean and subaqueous beds. Sand and gravel are products of the weathering of rocks and are mostly silica. Often, varied amounts of iron oxides, mica, feldspar and other minerals are present. Deposits are common throughout the country.

Depending upon the location of the deposit, the materials are excavated with power shovels, draglines, cableways, suction dredge pumps or other apparatus. Lightcharge blasting may occasionally be necessary to loosen the deposit. The materials are transported to the processing plant by suction pump, earth mover, barge, truck or other means. The processing of sand and gravel for a specific market involves the use of different combinations of washers, screens and classifiers to segregate particle sizes; crushers to reduce oversize material; and storage and loading facilities.

8.19.1.2 Emissions and Controls[1]

Dust emissions occur during conveying, screening, crushing and storing operations. Generally, these materials are wet or moist when handled, and process emissions are often negligible. (If processing is dry, expected emissions could be similar to those shown in Section 8.19.2, Crushed Stone.) Considerable emissions may occur from vehicles hauling materials to and from a site. Open dust source emission factors for such sand and gravel processing operations have been determined through source testing at various sand and gravel plants and, in some instances, through additional extrapolations, and are presented in Table 8.19.1-1.

As an alternative to the single valued emission factors given in Table 8.19.1-1, empirically derived emission factor equations are presented in Chapter 11 of this document. Each equation was developed for a single source operation or dust generating mechanism which crosses industry lines, such as vehicular traffic on unpaved roads. The predictive equation explains much of the observed variance in measured emission factors by relating emissions to different source parameters. These parameters may be grouped as 1) measures of source activity or expended energy (e.g., the speed and weight of a vehicle traveling on an unpaved road); 2) properties of the material being disturbed (e.g., the content of suspendable fines in the surface material on an unpaved road); and 3) climate (e.g., number of precipitation free days per year, when emissions tend to a maximum).

Because predictive equations allow for emission factor adjustment to specific conditions, they should be used instead of the factors given in Table 8.19.1-1 whenever emission estimates are needed for sources in a specific sand and gravel processing facility. However, the generally higher quality ratings assigned to the equations are applicable only if 1) reliable values of correction parameters have been determined for the specific

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TABLE 8.19.1-1. UNCONTROLLED PARTICULATE EMISSION FACTORS FOR OPEN DUST SOURCES AT SAND AND GRAVEL PROCESSING PLANTS[a]

Uncontrolled dry operation	Emissions by particle size range (aerodynamic diameter)[b]				Emission Factor Rating
	Total particulate	TSP < ~30 μm	< 10 μm	Units	
Continuous drop[c]					
Transfer station	0.014 (0.029)	NA	NA	kg/Mg (lb/ton)	E
Pile formation - stacker	NA	0.065 (0.13)	0.03 (0.06)[d]	kg/Mg (lb/ton)	E
Batch drop[c]					
Bulk loading	0.12 (0.24)	0.028 (0.056)[e]	0.0012 (0.0024)[e]	kg/Mg (lb/ton)	E
Active storage piles[f,g,h]					
Active day	NA	14.8 (13.2)	7.1 (6.3)[d]	kg/hectare/day (lb/acre/day)[i]	D
Inactive day (wind erosion only)	NA	3.9 (3.5)	1.9 (1.7)[d]	kg/hectare/day (lb/acre/day)[i]	D
Normal mix of active and inactive day[j]	NA	11.6 (10.4)	5.6 (5.0)[d]	kg/hectare/day (lb/acre/day)[i]	D
Vehicle traffic on unpaved road[c]					
Heavy duty vehicle	14.7 (52.0)	9.31 (33.0)[e]	0.87 (3.1)[e]	kg/VKT (lb/VMT)	C

[a] NA = not available. TSP = total suspended particulate. VKT = vehicle kilometers traveled. VMT = vehicle miles traveled. Predictive emission factor equations, which generally provide more accurate estimates of emissions, are presented in Chapter 11.

[b] Total particulate is airborne particles of all sizes in the source plume. TSP is what is measured by a standard high volume sampler (see Section 11.2).

[c] Reference 3.

[d] Extrapolation of data using k factors for appropriate operation from Chapter 11.

[e] For physical, not aerodynamic, diameter.

[f] Reference 4.

[g] Includes the following distinct source operations in the storage cycle: 1) loading of aggregate onto storage piles (batch or continuous drop operations), 2) equipment traffic in storage areas, 3) wind erosion of pile surfaces and ground areas among piles, and 4) loadout of aggregate for shipment or for return to the process stream (batch or continuous drop operations).

[h] 8 to 12 hours of activity per 24 hours.

[i] Pounds/acre of storage (includes areas among piles)/day.

[j] Assumes a 5 day work week.

sources of interest and 2) the correction parameter values lie within the ranges tested in developing the equations. Chapter 11 lists measured properties of aggregate materials used in industries relating to the sand and gravel industry, which can be used to approximate correction parameter values for the predictive emission factor equations, in the event that site specific values are not available. Use of mean correction parameter values from Chapter 11 reduces the quality ratings of the emission factor equations by at least one level.

Since emissions from sand and gravel operations are usually in the form of fugitive dust, control techniques applicable to fugitive dust sources are appropriate. Control techniques most successfully used[1] for haul roads are application of dust suppressants, paving, route modifications, soil stabilization, etc.; for conveyors, covering and wet dust suppression; for storage piles, wet dust suppression, windbreaks, enclosure and soil stabilizers; and for conveyor and batch transfer points (loading, unloading, etc.), wet suppression and various methods to reduce freefall distances (e.g., telescopic chutes, stone ladders and hinged boom stacker conveyors).

Wet suppression techniques include application of water, chemicals or foam, usually at conveyor feed and discharge points. Such spray systems at transfer points and on material handling operations are estimated to reduce emissions 70 to 95 percent.[5] Spray systems can also reduce loading and wind erosion emissions from storage piles of various materials 80 to 90 percent.[6] Control efficiencies depend upon local climatic conditions, source properties and duration of control effectiveness. Table 11.2.1-2 contains estimates of control efficiency for various emission suppressant methods for haul roads.

References for Section 8.19.1

1. Air Pollution Control Techniques for Nonmetallic Minerals Industry, U. S. Environmental Protection Agency, Research Triangle Park, NC, August 1982.

2. S. Walker, "Production of Sand and Gravel", Circular Number 57, National Sand and Gravel Association, Washington, DC, 1954.

3. Fugitive Dust Assessment at Rock and Sand Facilities in the South Coast Air Basin, Southern California Rock Products Association and Southern California Ready Mix Concrete Association, Santa Monica, CA, November 1979.

4. C. Cowherd, Jr., et al., Development of Emission Factors for Fugitive Dust Sources, EPA-450/3-74-037, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

5. R. Bohn, et al., Fugitive Emissions from Integrated Iron and Steel Plants, EPA-600/2-78-050, U. S. Environmental Protection Agency, Washington, DC, March 1978.

6. G. A. Jutze, and K. Axetell, *Investigation of Fugitive Dust, Volume I: Sources, Emissions and Control*, EPA-450/3-74-036a, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

8.22 TACONITE ORE PROCESSING

8.22.1 General[1-2]

More than two thirds of the iron ore produced in the United States for making iron consists of taconite concentrate pellets. Taconite is a low grade iron ore, largely from deposits in Minnesota and Michigan, but from other areas as well. Processing of taconite consists of crushing and grinding the ore to liberate ironbearing particles, concentrating the ore by separating the particles from the waste material (gangue), and pelletizing the iron ore concentrate. A simplified flow diagram of these processing steps is shown in Figure 8.22-1.

Liberation - The first step in processing crude taconite ore is crushing and grinding. The ore must be ground to a particle size sufficiently close to the grain size of the ironbearing mineral, to allow for a high degree of mineral liberation. Most of the taconite used today requires very fine grinding. The grinding is normally performed in three or four stages of dry crushing, followed by wet grinding in rod mills and ball mills. Gyratory crushers are generally used for primary crushing, and cone crushers are used for secondary and tertiary fine crushing. Intermediate vibrating screens remove undersize material from the feed to the next crusher and allow for closed circuit operation of the fine crushers. The rod and ball mills are also in closed circuit with classification systems such as cyclones. An alternative is to feed some coarse ores directly to wet or dry semiautogenous or autogenous grinding mills, then to pebble or ball mills. Ideally, the liberated particles of iron minerals and barren gangue should be removed from the grinding circuits as soon as they are formed, with larger particles returned for further grinding.

Concentration - As the iron ore minerals are liberated by the crushing steps, the ironbearing particles must be concentrated. Since only about 33 percent of the crude taconite becomes a shippable product for iron making, a large amount of gangue is generated. Magnetic separation and flotation are most commonly used for concentration of the taconite ore.

Crude ores in which most of the recoverable iron is magnetite (or, in rare cases, maghemite) are normally concentrated by magnetic separation. The crude ore may contain 30 to 35 percent total iron by assay, but theoretically only about 75 percent of this is recoverable magnetite. The remaining iron becomes part of the gangue.

Nonmagnetic taconite ores are concentrated by froth flotation or by a combination of selective flocculation and flotation. The method is determined by the differences in surface activity between the iron and gangue particles. Sharp separation is often difficult.

Various combinations of magnetic separation and flotation may be used to concentrate ores containing various iron minerals (magnetite and hematite, or maghemite) or wide ranges of mineral grain sizes. Flotation is also often used as a final polishing operation on magnetic concentrates.

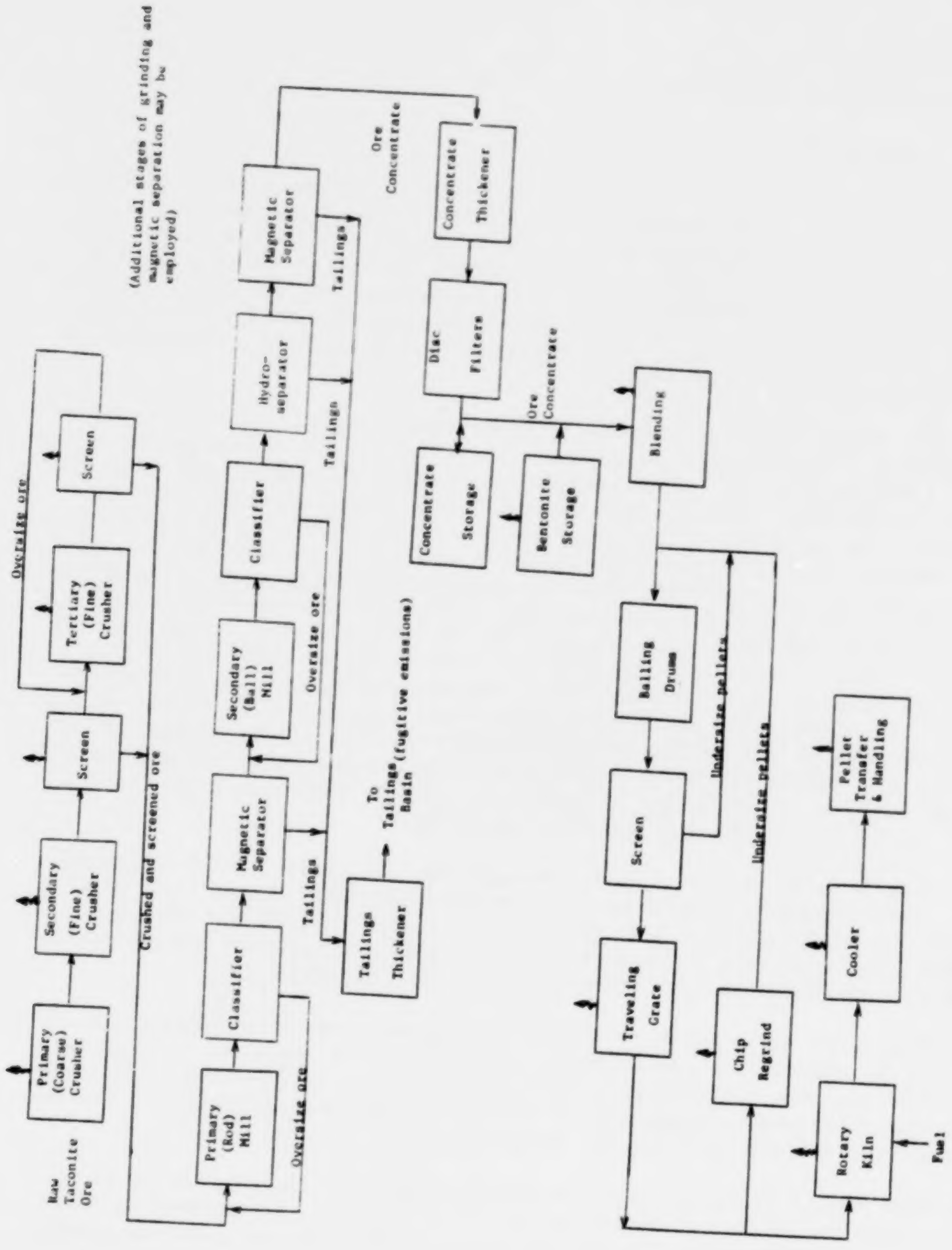

Figure 8.22-1. Taconite ore processing plant. (Process emissions are indicated by ↑.)

Pelletization - Iron ore concentrates must be coarser than about No. 10 mesh to be acceptable as blast furnace feed without further treatment. The finer concentrates are agglomerated into small "green" pellets. This is normally accomplished by tumbling moistened concentrate with a balling drum or balling disc. A binder additive, usually powdered bentonite, may be added to the concentrate to improve ball formation and the physical qualities of the "green" balls. The bentonite is lightly mixed with the carefully moistened feed at 4.5 to 9 kilograms per megagram (10 to 20 lb/ton).

The pellets are hardened by a procedure called induration, the drying and heating of the green balls in an oxidizing atmosphere at incipient fusion temperature [1290 to 1400°C (2350 to 2550°F), depending on the composition of the balls] for several minutes and then cooling. Four general types of indurating apparatus are currently used. These are the vertical shaft furnace, the straight grate, the circular grate and grate/kiln. Most of the large plants and new plants use the grate/kiln. Natural gas is most commonly used for pellet induration now, but probably not in the future. Heavy oil is being used at a few plants, and coal may be used at future plants.

In the vertical shaft furnace, the wet green balls are distributed evenly over the top of the slowly descending bed of pellets. A rising stream of gas of controlled temperature and composition flows counter to the descending bed of pellets. Auxiliary fuel combustion chambers supply hot gases midway between the top and bottom of the furnace. In the straight grate apparatus, a continuous bed of agglomerated green pellets is carried through various up and down flows of gases at different temperatures. The grate/kiln apparatus consists of a continuous traveling grate followed by a rotary kiln. Pellets indurated by the straight grate apparatus are cooled on an extension of the grate or in a separate cooler. The grate/kiln product must be cooled in a separate cooler, usually an annular cooler with countercurrent airflow.

8.22.2 Emissions and Controls[1-3]

Emission sources in taconite ore processing plants are indicated in Figure 8.22-1. Particulate emissions also arise from ore mining operations. Uncontrolled emission factors for the major processing sources are presented in Table 8.22-1, and control efficiencies in Table 8.22-2.

The taconite ore is handled dry through the crushing stages. All crushers, size classification screens and conveyor transfer points are major points of particulate emissions. Crushed ore is normally ground in wet rod and ball mills. A few plants, however, use dry autogenous or semiautogenous grinding and have higher emissions than do conventional plants. The ore remains wet through the rest of the beneficiation process, so particulate emissions after crushing are generally insignificant.

The first source of emissions in the pelletizing process is the transfer and blending of bentonite. There are no other significant emissions in the balling section, since the iron ore concentrate is normally too wet to cause appreciable dusting. Additional emission points in the pelletizing process include the main waste gas stream from the indurating furnace,

TABLE 8.22-1. UNCONTROLLED PARTICULATE EMISSION FACTORS FOR TACONITE ORE PROCESSING[a]

EMISSION FACTOR RATING: D

Source	Emissions[b]	
	kg/Mg	lb/ton
Fine crushing	39.9	79.8
Waste gas	14.6	29.2
Pellet handling	1.7	3.4
Grate discharge	0.66	1.32
Grate feed	0.32	0.64
Bentonite blending	0.11	0.22
Coarse crushing	0.10	0.20
Ore transfer	0.05	0.10
Bentonite transfer	0.02	0.04

[a] Reference 1. Median values.

[b] Expressed as units per unit weight of pellets produced.

pellet handling, furnace transfer points (grate feed and discharge), and for plants using the grate/kiln furnace, annular coolers. In addition, tailings basins and unpaved roadways can be sources of fugitive emissions.

Fuel used to fire the indurating furnace generates low levels of sulfur dioxide emissions. For a natural gas fired furnace, these emissions are about 0.03 kilograms of SO_2 per megagram of pellets produced (0.06 lb/ton). Higher SO_2 emissions (about 0.6 to 0.7 kg/Mg, or 0.12 to 0.14 lb/ton) would result from an oil or coal fired furnace.

Particulate emissions from taconite ore processing plants are controlled by a variety of devices, including cyclones, multiclones, rotoclones, scrubbers, baghouses and electrostatic precipitators. Water sprays are also used to suppress dusting. Annular coolers are generally left uncontrolled, because their mass loadings of particulates are small, typically less than 0.11 grams per cubic meter (0.05 g/scf).

The largest source of particulate emissions in taconite ore mines is traffic on unpaved haul roads.[3] Table 8.22-3 presents size specific emission factors for this source determined through source testing at one taconite mine. Other significant particulate emission sources at taconite mines are wind erosion and blasting.[3]

As an alternative to the single valued emission factors for open dust sources given in Tables 8.22-1 and 8.22-3, empirically derived emission

TABLE 8.22-2. CONTROL EFFICIENCIES FOR COMBINATIONS OF CONTROL DEVICES AND SOURCES[a]

Control	Coarse crushing	Ore transfer	Fine crushing	Bentonite transfer	Bentonite blending	Grate feed	Grate discharge	Waste gas	Pellet handling
Scrubber	95(10)f 91.6(4)f 99(2)m	99.5(18)f 99(5)f 97(4)m 99(1)m	99.5(5)f 99.6(6)f 97(10)m 97(19)e	98(1)f	98.7(1)f 99.3(1)f	98.7(2)f 98(1)m 99(5)e	99.3(2)f 99(5)e 98(1)e	98.5(1)e 89(1)e	99.3(2)f 99.7(1)f 99(2)f 97.5(1)e
Cyclone	85(1)f	95(2)e						95-98(56)f	
Multiclone	92(2)f 88(2)f							95-98(2)f	
Rotoclone	91.6(4)f	98(1)f	99.7(7)f 98.3(4)f						98(1)e
Bag collector	99(2)m 99.9(2)m 99(4)e 99.9(2)e			99(8)e	99(2)f 99.7(1)f				
Electrostatic precipitator								98.9(2)f 98.8(1)e	
Dry mechanical collector	85(1)f	85(1)f							
Centrifugal collector						88(1)f 98(1)e 99.4(1)e	88(1)f 99.4(1)e		

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[a] Reference 1. Control efficiencies are expressed as percent reduction. Numbers in parentheses are the number of indicated combinations with the stated efficiency. The letters m, f, e denote whether the stated efficiencies were based upon manufacturer's rating (m), field testing (f), or estimations (e). Blanks indicate that no such combinations of source and control technology are known to exist, or that no data on the efficiency of the combination are available.

TABLE 8.22-3. UNCONTROLLED PARTICULATE EMISSION FACTORS FOR HEAVY DUTY VEHICLE TRAFFIC ON HAUL ROADS AT TACONITE MINES[a]

Surface material	Emission factor by aerodynamic diameter					Units	Emission Factor Rating
	< 30 μm	< 15 μm	< 10 μm	< 5 μm	< 2.5 μm		
Crushed rock and glacial till	3.1	2.2	1.7	1.1	0.62	kg/VKT	C
	11.0	7.9	6.2	3.9	2.2	lb/VMT	C
Crushed taconite and waste	2.6	1.9	1.5	0.90	0.54	kg/VKT	D
	9.3	6.6	5.2	3.2	1.9	lb/VMT	D

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[a] Reference 3. Predictive emission factor equations, which generally provide more accurate estimates of emissions, are presented in Chapter 11. VKT = Vehicle kilometers traveled. VMT = Vehicle miles traveled.

factor equations are presented in Chapter 11 of this document. Each equation was developed for a source operation defined on the basis of a single dust generating mechanism which crosses industry lines, such as vehicle traffic on unpaved roads. The predictive equation explains much of the observed variance in measured emission factors by relating emissions to parameters which characterize source conditions. These parameters may be grouped into three categories: 1) measures of source activity or energy expended (e.g., the speed and weight of a vehicle traveling on an unpaved road), 2) properties of the material being disturbed (e.g., the content of suspendable fines in the surface material on an unpaved road), 3) climatic parameters (e.g., number of precipitation free days per year, when emissions tend to a maximum).

Because the predictive equations allow for emission factor adjustment to specific source conditions, the equations should be used in place of the single valued factors for open dust sources, in Tables 8.22-1 and 8.22-3, if emission estimates for sources in a specific taconite ore mine or processing facility are needed. However, the generally higher quality ratings assigned to the equations are applicable only if 1) reliable values of correction parameters have been determined for the specific sources of interest and 2) the correction parameter values lie within the ranges tested in developing the equations. Chapter 11 lists measured properties of aggregate process materials and road surface materials found in taconite mining and processing facilities, which can be used to estimate correction parameter values for the predictive emission factor equations, in the event that site specific values are not available. Use of mean correction parameter values from Chapter 11 reduces the quality ratings of the emission factor equations by one level.

References for Section 8.22

1. J. P. Pilney and G. V. Jorgensen, Emissions from Iron Ore Mining, Beneficiation and Pelletization, Volume 1, EPA Contract No. 68-02-2113, Midwest Research Institute, Minnetonka, MN, June 1978.

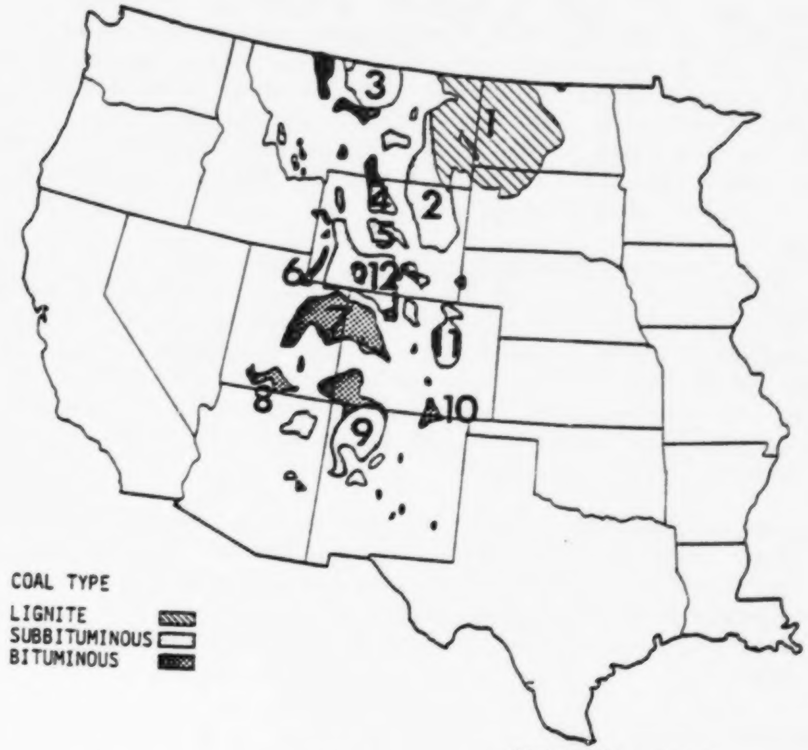
2. A. K. Reed, Standard Support and Environmental Impact Statement for the Iron Ore Beneficiation Industry (Draft), EPA Contract No. 68-02-1323, Battelle Columbus Laboratories, Columbus, OH, December 1976.

3. T. A. Cuscino, et al., Taconite Mining Fugitive Emissions Study, Minnesota Pollution Control Agency, Roseville, MN, June 1979.

8.24 WESTERN SURFACE COAL MINING

8.24.1 General[1]

There are 12 major coal fields in the western states (excluding the Pacific Coast and Alaskan fields), as shown in Figure 8.24-1. Together, they account for more than 64 percent of the surface minable coal reserves



	Coal field	Strippable reserves (10^6 tons)
1	Fort Union	23,529
2	Powder River	56,727
3	North Central	All underground
4	Bighorn Basin	All underground
5	Wind River	3
6	Hams Fork	1,000
7	Uinta	308
8	Southwestern Utah	224
9	San Juan River	2,318
10	Raton Mesa	All underground
11	Denver	All underground
12	Green River	2,120

Figure 8.24-1. Coal fields of the western U.S.[3]

in the United States.[2] The 12 coal fields have varying characteristics which may influence fugitive dust emission rates from mining operations, including overburden and coal seam thicknesses and structure, mining equipment, operating procedures, terrain, vegetation, precipitation and surface moisture, wind speeds and temperatures. The operations at a typical western surface mine are shown in Figure 8.24-2. All operations that involve movement of soil, coal, or equipment, or exposure of erodible surfaces, generate some amount of fugitive dust.

The initial operation is removal of topsoil and subsoil with large scrapers. The topsoil is carried by the scrapers to cover a previously mined and regraded area as part of the reclamation process or is placed in temporary stockpiles. The exposed overburden, the earth which is between the topsoil and the coal seam, is leveled, drilled and blasted. Then the overburden material is removed down to the coal seam, usually by a dragline or a shovel and truck operation. It is placed in the adjacent mined cut, forming a spoils pile. The uncovered coal seam is then drilled and blasted. A shovel or front end loader loads the broken coal into haul trucks, and it is taken out of the pit along graded haul roads to the tipple, or truck dump. Raw coal sometimes may be dumped onto a temporary storage pile and later rehandled by a front end loader or bulldozer.

At the tipple, the coal is dumped into a hopper that feeds the primary crusher, then is conveyed through additional coal preparation equipment such as secondary crushers and screens to the storage area. If the mine has open storage piles, the crushed coal passes through a coal stacker onto the pile. The piles, usually worked by bulldozers, are subject to wind erosion. From the storage area, the coal is conveyed to a train loading facility and is put into rail cars. At a captive mine, coal will go from the storage pile to the power plant.

During mine reclamation, which proceeds continuously throughout the life of the mine, overburden spoils piles are smoothed and contoured by bulldozers. Topsoil is placed on the graded spoils, and the land is prepared for revegetation by furrowing, mulching, etc. From the time an area is disturbed until the new vegetation emerges, all disturbed areas are subject to wind erosion.

8.24.2 Emissions

Predictive emission factor equations for open dust sources at western surface coal mines are presented in Tables 8.24-1 and 8.24-2. Each equation is for a single dust generating activity, such as vehicle traffic on unpaved roads. The predictive equation explains much of the observed variance in emission factors by relating emissions to three sets of source parameters: 1) measures of source activity or energy expended (e.g., speed and weight of a vehicle traveling on an unpaved road); 2) properties of the material being disturbed (e.g., suspendable fines in the surface material of an unpaved road); and 3) climate (in this case, mean wind speed).

The equations may be used to estimate particulate emissions generated per unit of source extent (e.g., vehicle distance traveled or mass of material transferred).

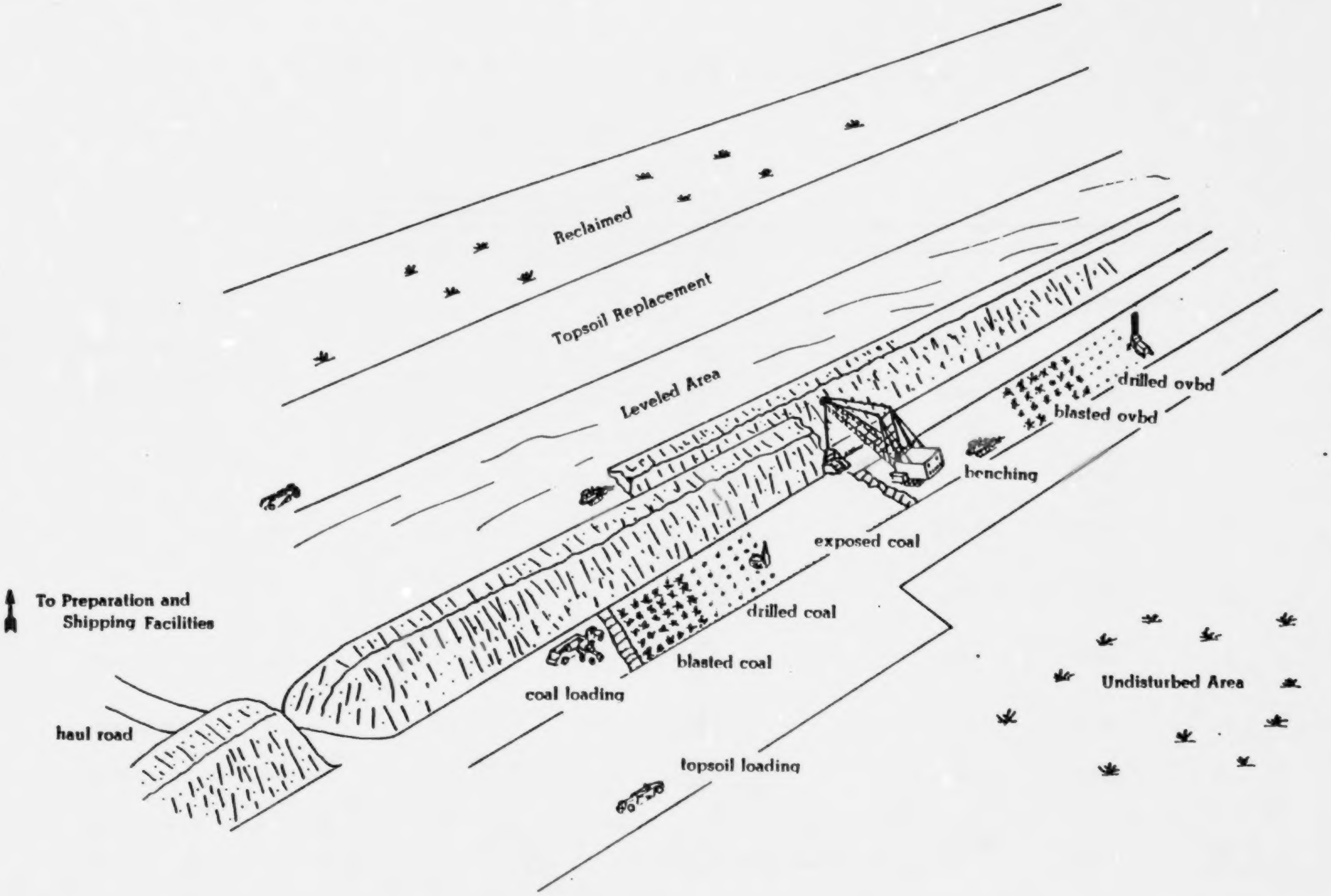


Figure 8.24-2. Operations at typical western surface coal mines.

TABLE 8.24-1. EMISSION FACTOR EQUATIONS FOR UNCONTROLLED OPEN DUST SOURCES AT WESTERN SURFACE COAL MINES (METRIC UNITS)[a]

Operation	Material	Emissions by particle size range (aerodynamic diameter)[b,c] TSP (< ~ 30 μm)	< 15 μm	< 2.5 μm/TSP[d]	Units	Emission Factor Rating
Blasting	Coal or overburden	$\frac{344\ (A)^{0.8}}{(D)^{1.8}\ (M)^{1.9}}$	$\frac{811\ (A)^{0.6}}{(D)^{1.5}\ (M)^{2.3}}$	0.030	kg/blast	B
Truck loading	Coal	$\frac{0.580}{(M)^{1.2}}$	$\frac{0.0596}{(M)^{0.9}}$	0.019	kg/Mg	B
Bulldozing	Coal	$\frac{35.6\ (s)^{1.2}}{(M)^{1.3}}$	$\frac{8.44\ (s)^{1.5}}{(M)^{1.4}}$	0.022	kg/hr	B
	Overburden	$\frac{2.6\ (s)^{1.2}}{(M)^{1.3}}$	$\frac{0.45\ (s)^{1.5}}{(M)^{1.4}}$	0.105	kg/hr	B
Dragline	Overburden	$\frac{0.0046\ (d)^{1.1}}{(M)^{0.3}}$	$\frac{0.0029\ (d)^{0.7}}{(M)^{0.3}}$	0.017	kg/m³	B
Scrapers (travel mode)		$9.6 \times 10^{-6}\ (s)^{1.3}\ (W)^{2.4}$	$2.2 \times 10^{-6}\ (s)^{1.4}\ (W)^{2.5}$	0.026	kg/VKT	A
Grading		$0.0034\ (S)^{2.5}$	$0.0056\ (S)^{2.0}$	0.031	kg/VKT	B
Vehicle traffic (light/medium duty)		$\frac{1.63}{(M)^{4.0}}$	$\frac{1.05}{(M)^{4.3}}$	0.040	kg/VKT	B
Haul trucks		$0.0019\ (w)^{3.4}\ (L)^{0.2}$	$0.0014\ (w)^{3.5}$	0.017	kg/VKT	A
Active storage pile (wind erosion and maintenance)	Coal	1.8 u	NA	NA	$\frac{kg}{(hectare)(hr)}$	C[e]

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[a] All equations are from Reference 1, except for coal storage pile equation from Reference 4. TSP = total suspended particulate. VMT = vehicle miles traveled. VKT = vehicle kilometers traveled. NA = not available.

[b] TSP denotes what is measured by a standard high volume sampler (see Section 11.2).

[c] Symbols for equations:

A = area blasted (m²)
M = material moisture content (%)
D = hole depth (m)
s = material silt content (%)
u = wind speed (m/sec)
d = drop height (m)
W = mean vehicle weight (Mg)
S = mean vehicle speed (kph)
w = mean number of wheels
L = road surface silt loading (g/m²)

[d] Multiply the TSP predictive equation by this fraction to determine emissions in the < 2.5 μm size range.

[e] Rating applicable to Mine Types I, II and IV (see Tables 8.24-5 and 8.24-6).

TABLE 8.24-2. EMISSION FACTOR EQUATIONS FOR UNCONTROLLED OPEN DUST SOURCES AT WESTERN SURFACE COAL MINES (ENGLISH UNITS)[a]

Operation	Material	Emissions by particle size range (aerodynamic diameter)[b,c]			Units	Emission Factor Rating
		TSP (< ~ 30 μm)	< 15 μm	< 2.5 μm/TSP[d]		
Blasting	Coal or overburden	$\frac{961\ (A)^{0.8}}{(D)^{1.8}\ (M)^{1.9}}$	$\frac{2{,}550\ (A)^{0.6}}{(D)^{1.5}\ (M)^{2.3}}$	0.030	lb/blast	B
Truck loading	Coal	$\frac{1.16}{(M)^{1.2}}$	$\frac{0.119}{(M)^{0.9}}$	0.019	lb/T	B
Bulldozing	Coal	$\frac{78.4\ (s)^{1.2}}{(M)^{1.3}}$	$\frac{18.6\ (s)^{1.5}}{(M)^{1.4}}$	0.022	lb/hr	B
	Overburden	$\frac{5.7\ (s)^{1.2}}{(M)^{1.3}}$	$\frac{1.0\ (s)^{1.5}}{(M)^{1.4}}$	0.105	lb/hr	B
Dragline	Overburden	$\frac{0.0021\ (d)^{1.1}}{(M)^{0.3}}$	$\frac{0.0021\ (d)^{0.7}}{(M)^{0.3}}$	0.017	lb/yd³	B
Scrapers (travel mode)		$2.7 \times 10^{-5}\ (s)^{1.3}\ (W)^{2.4}$	$6.2 \times 10^{-6}\ (s)^{1.4}\ (W)^{2.5}$	0.026	lb/VMT	A
Grading		$0.040\ (S)^{2.5}$	$0.051\ (S)^{2.0}$	0.031	lb/VMT	B
Vehicle traffic (light/medium duty)		$\frac{5.79}{(M)^{4.0}}$	$\frac{3.72}{(M)^{4.3}}$	0.040	lb/VMT	B
Haul trucks		$0.0067\ (w)^{3.4}\ (L)^{0.2}$	$0.0051\ (w)^{3.5}$	0.017	lb/VMT	A
Active storage pile (wind erosion and maintenance)	Coal	1.6 u	NA	NA	$\frac{\text{lb}}{(\text{acre})(\text{hr})}$	C[e]

[a] All equations are from Reference 1, except for coal storage pile equation from Reference 4. TSP = total suspended particulate. VMT = vehicle miles traveled. VKT = vehicle kilometers traveled. NA = not available.

[b] TSP denotes what is measured by a standard high volume sampler (see Section 11.2).

[c] Symbols for equations:

A = area blasted (ft²)
M = material moisture content (%)
D = hole depth (ft)
s = material silt content (%)
u = wind speed (m/sec)
d = drop height (ft)
W = mean vehicle weight (tons)
S = mean vehicle speed (mph)
w = mean number of wheels
L = road surface silt loading (g/m²)

[d] Multiply the TSP predictive equation by this fraction to determine emissions in the < 2.5 μm size range.

[e] Rating applicable to Mine Types I, II and IV (see Tables 8.24-5 and 8.24-6).

The equations were developed through field sampling various western surface mine types and are thus applicable to any of the surface coal mines located in the western United States.

In Tables 8.24-1 and 8.24-2, the assigned quality ratings apply within the ranges of source conditions that were tested in developing the equations, given in Table 8.24-3. However, the equations are derated one letter value (e.g., A to B) if applied to eastern surface coal mines.

TABLE 8.24-3. TYPICAL VALUES FOR CORRECTION FACTORS APPLICABLE TO THE PREDICTIVE EMISSION FACTOR EQUATIONS[a]

Source	Correction factor	Number of test samples	Range	Geometric mean	Units
Blasting	Moisture	5	7.2 - 38	17.2	%
	Depth	18	6 - 41	7.9	m
			20 - 135	25.9	ft
	Area	18	90 - 9,000	1,800	m^2
			1,000 - 100,000	19,000	ft^2
Coal loading	Moisture	7	6.6 - 38	17.8	%
Bulldozers					
Coal	Moisture	3	4.0 - 22.0	10.4	%
	Silt	3	6.0 - 11.3	8.6	%
Overburden	Moisture	8	2.2 - 16.8	7.9	%
	Silt	8	3.8 - 15.1	6.9	%
Dragline	Drop distance	19	1.5 - 30	8.6	m
			5 - 100	28.1	ft
	Moisture	7	0.2 - 16.3	3.2	%
Scraper	Silt	10	7.2 - 25.2	16.4	%
	Weight	15	33 - 64	48.8	Mg
			36 - 70	53.8	tons
Grader	Speed	7	8.0 - 19.0	11.4	kph
			5.0 - 11.8	7.1	mph
Light/medium duty vehicles	Moisture	7	0.9 - 1.7	1.2	%
Haul truck	Wheels	29	6.1 - 10.0	8.1	number
	Silt loading	26	3.8 - 254	40.8	g/m^2
			34 - 2,270	364	lb/acre

[a] Reference 1.

In using the equations to estimate emissions from sources in a specific western surface coal mine, it is necessary that reliable values for correction parameters be determined for the specific sources of interest, if the assigned quality ratings of the equations are to apply. For example, actual silt content of coal or overburden measured at a facility should be used instead of estimated values. In the event that site specific values for correction parameters cannot be obtained, the appropriate geometric mean values from Table 8.24-3 may be used, but the assigned quality rating of each emission factor equation is reduced by one level (e.g., A to B).

Emission factors for open dust sources not covered in Table 8.24-3 are in Table 8.24-4. These factors were determined through source testing at various western coal mines.

The factors in Table 8.24-4 for mine locations I through V were developed for specific geographical areas. Tables 8.24-5 and 8.24-6 present characteristics of each of these mines (areas). A "mine specific" emission factor should be used only if the characteristics of the mine for which an emissions estimate is needed are very similar to those of the mine for which the emission factor was developed. The other (nonspecific) emission factors were developed at a variety of mine types and thus are applicable to any western surface coal mine.

As an alternative to the single valued emission factors given in Table 8.24-4 for train or truck loading and for truck or scraper unloading, two empirically derived emission factor equations are presented in Section 11.2.3 of this document. Each equation was developed for a source operation (i.e., batch drop and continuous drop, respectively), comprising a single dust generating mechanism which crosses industry lines.

Because the predictive equations allow emission factor adjustment to specific source conditions, the equations should be used in place of the factors in Table 8.24-4 for the sources identified above, if emission estimates for a specific western surface coal mine are needed. However, the generally higher quality ratings assigned to the equations are applicable only if 1) reliable values of correction parameters have been determined for the specific sources of interest and 2) the correction parameter values lie within the ranges tested in developing the equations. Table 8.24-3 lists measured properties of aggregate materials which can be used to estimate correction parameter values for the predictive emission factor equations in Chapter 11, in the event that site specific values are not available. Use of mean correction parameter values from Table 8.24-3 reduces the quality ratings of the emission factor equations in Chapter 11 by one level.

TABLE 8.24-4. UNCONTROLLED PARTICULATE EMISSION FACTORS FOR OPEN DUST SOURCES AT WESTERN SURFACE COAL MINES

Source	Material	Mine location[a]	TSP emission factor[b]	Units	Emission Factor Rating
Drilling	Overburden	Any	1.3	lb/hole	B
			0.59	kg/hole	B
	Coal	V	0.22	lb/hole	E
			0.10	kg/hole	E
Topsoil removal by scraper	Topsoil	Any	0.058	lb/T	E
			0.029	kg/Mg	E
		IV	0.44	lb/T	D
			0.22	kg/Mg	D
Overburden replacement	Overburden	Any	0.012	lb/T	C
			0.0060	kg/Mg	C
Truck loading by power shovel (batch drop)[c]	Overburden	V	0.037	lb/T	C
			0.018	kg/Mg	C
Train loading (batch or continuous drop)[c]	Coal	Any	0.028	lb/T	D
			0.014	kg/Mg	D
		III	0.0002	lb/T	D
			0.0001	kg/Mg	D
Bottom dump truck unloading (batch drop)[c]	Overburden	V	0.002	lb/T	E
			0.001	kg/T	E
	Coal	IV	0.027	lb/T	E
			0.014	kg/Mg	E
		III	0.005	lb/T	E
			0.002	kg/Mg	E
		II	0.020	lb/T	F
			0.010	kg/Mg	E
		I	0.014	lb/T	D
			0.0070	kg/Mg	D
		Any	0.066	lb/T	D
			0.033	kg/Mg	D
End dump truck unloading (batch drop)[c]	Coal	V	0.007	lb/T	E
			0.004	kg/Mg	E
Scraper unloading (batch drop)[c]	Topsoil	IV	0.04	lb/T	C
			0.02	kg/Mg	C
Wind erosion of exposed areas	Seeded land, stripped overburden, graded overburden	Any	0.38	$\frac{T}{(acre)(yr)}$	C
			0.85	$\frac{Mg}{(hectare)(yr)}$	C

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[a] Roman numerals I through V refer to specific mine locations for which the corresponding emission factors were developed (Reference 4). Tables 8.24-4 and 8.24-5 present characteristics of each of these mines. See text for correct use of these "mine specific" emission factors. The other factors (from Reference 5 except for overburden drilling from Reference 1) can be applied to any western surface coal mine.

[b] Total suspended particulate (TSP) denotes what is measured by a standard high volume sampler (see Section 11.2).

[c] Predictive emission factor equations, which generally provide more accurate estimates of emissions, are presented in Chapter 11.

TABLE 8.24-5. GENERAL CHARACTERISTICS OF SURFACE COAL MINES REFERRED TO IN TABLE 8.24-4[a]

Mine	Location	Type of coal mined	Terrain	Vegetative cover	Surface soil type and erodibility index	Mean wind speed		Mean annual precipitation	
						m/s	mph	cm	in.
I	N.W. Colorado	Subbitum.	Moderately steep	Moderate, sagebrush	Clayey, loamy (71)	2.3	5.1	38	15
II	S.W. Wyoming	Subbitum.	Semirugged	Sparse, sagebrush	Arid soil with clay and alkali or carbonate accumulation (86)	6.0	13.4	36	14
III	S.E. Montana	Subbitum.	Gently rolling to semirugged	Sparse, moderate, prairie grassland	Shallow clay loamy deposits on bedrock (47)	4.8	10.7	28 - 41	11 - 16
IV	Central North Dakota	Lignite	Gently rolling	Moderate, prairie grassland	Loamy, loamy to sandy (71)	5.0	11.2	43	17
V	N.E. Wyoming	Subbitum.	Flat to gently rolling	Sparse, sagebrush	Loamy, sandy, clayey, and clay loamy (102)	6.0	13.4	36	14

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[a] Reference 4.

TABLE 8.24-6. OPERATING CHARACTERISTICS OF THE COAL MINES REFERRED TO IN TABLE 8.24-4[a]

Parameter	Required information	Units	Mine I	Mine II	Mine III	Mine IV	Mine V
Production rate	Coal mined	10^6 T/yr	1.13	5.0	9.5	3.8	12.0[b]
Coal transport	Avg. unit train frequency	per day	NA	NA	2	NA	2
Stratigraphic data	Overburden thickness	ft	21	80	90	65	35
	Overburden density	lb/yd^3	4000	3705	3000	-	-
	Coal seam thicknesses	ft	9,35	15,9	27	2,4,8	70
	Parting thicknesses	ft	50	15	NA	32,16	NA
	Spoils bulking factor	%	22	24	25	20	-
	Active pit depth	ft	52	100	114	80	105
Coal analysis data	Moisture	%	10	18	24	38	30
	Ash	%, wet	8	10	8	7	6
	Sulfur	%, wet	0.46	0.59	0.75	0.65	0.48
	Heat content	Btu/lb	11000	9632	8628	8500	8020
Surface disposition	Total disturbed land	acre	168	1030	2112	1975	217
	Active pit	acre	34	202	87	-	71
	Spoils	acre	57	326	144	-	100
	Reclaimed	acre	100	221	950	-	100
	Barren land	acre	-	30	455	-	-
	Associated disturbances	acre	12	186	476	-	46
Storage	Capacity	ton	NA	NA	-	NA	48000
Blasting	Frequency, coal	per week	4	4	3	7	7[b]
	Frequency, overburden	per week	3	0.5	3	NA	7[b]
	Area blasted, coal	ft^2	16000	40000	-	30000	-
	Area blasted, overburden	ft^2	20000	-	-	NA	-

[a] Reference 4. NA = not applicable. Dash = not available.
[b] Estimate.

References for Section 8.24

1. K. Axetell and C. Cowherd, Improved Emission Factors for Fugitive Dust from Western Surface Coal Mining Sources, 2 Volumes, EPA Contract No. 68-03-2924, U. S. Environmental Protection Agency, Cincinnati, OH, July 1981.

2. Reserve Base of U. S. Coals by Sulfur Content: Part 2, The Western States, IC8693, Bureau of Mines, U. S. Department of the Interior, Washington, DC, 1975.

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4. K. Axetell, Survey of Fugitive Dust from Coal Mines, EPA-908/1-78-003, U. S. Environmental Protection Agency, Denver, CO, February 1978.

5. J. L. Shearer, et al., Coal Mining Emission Factor Development and Modeling Study, Amax Coal Company, Carter Mining Company, Sunoco Energy Development Company, Mobil Oil Corporation, and Atlantic Richfield Company, Denver, CO, July 1981.

11.2 FUGITIVE DUST SOURCES

Significant atmospheric dust arises from the mechanical disturbance of granular material exposed to the air. Dust generated from these open sources is termed "fugitive" because it is not discharged to the atmosphere in a confined flow stream. Common sources of fugitive dust include unpaved roads, agricultural tilling operations, aggregate storage piles, and heavy construction operations.

For the above categories of fugitive dust sources, the dust generation process is caused by two basic physical phenomena:

1. Pulverization and abrasion of surface materials by application of mechanical force through implements (wheels, blades, etc.).

2. Entrainment of dust particles by the action of turbulent air currents, such as wind erosion of an exposed surface by wind speeds over 19 kilometers per hour (12 miles/hr).

The air pollution impact of a fugitive dust source depends on the quantity and drift potential of the dust particles injected into the atmosphere. In addition to large dust particles that settle out near the source (often creating a local nuisance problem), considerable amounts of fine particles are also emitted and dispersed over much greater distances from the source.

The potential drift distance of particles is governed by the initial injection height of the particle, the particle's terminal settling velocity, and the degree of atmospheric turbulence. Theoretical drift distances, as a function of particle diameter and mean wind speed, have been computed for fugitive dust emissions.[1] These results indicate that, for a typical mean wind speed of 16 kilometers per hour (10 miles/hr), particles larger than about 100 micrometers are likely to settle out within 6 to 9 meters (20 to 30 ft) from the edge of the road. Particles that are 30 to 100 micrometers in diameter are likely to undergo impeded settling. These particles, depending upon the extent of atmospheric turbulence, are likely to settle within a few hundred feet from the road. Smaller particles, particularly those less than 10 to 15 micrometers in diameter, have much slower gravitational settling velocities and are much more likely to have their settling rate retarded by atmospheric turbulence. Thus, based on the presently available data, it appears appropriate to report only those particles smaller than 30 micrometers. Future updates to this document are expected to define appropriate factors for other particle sizes.

Several of the emission factors presented in this Section are expressed in terms of total suspended particulate (TSP). TSP denotes what is measured by a standard high volume sampler. Recent wind tunnel studies have shown that the particle mass capture efficiency curve for the high volume sampler is very broad, extending from 100 percent capture of particles smaller than 10 micrometers to a few percent capture of particles as large as 100 micrometers. Also, the capture efficiency curve varies with wind speed and wind direction, relative to roof ridge orientation. Thus, high volume samplers do not provide definitive particle size information for emission factors. However, an effective cutpoint of 30 micrometers aerodynamic diameter is frequently assigned to the standard high volume sampler.

Control techniques for fugitive dust sources generally involve watering, chemical stabilization, or reduction of surface wind speed with windbreaks or source enclosures. Watering, the most common and generally least expensive method, provides only temporary dust control. The use of chemicals to treat exposed surfaces provides longer dust suppression but may be costly, have adverse effects on plant and animal life, or contaminate the treated material. Windbreaks and source enclosures are often impractical because of the size of fugitive dust sources.

11.2.1 UNPAVED ROADS

11.2.1.1 General

Dust plumes trailing behind vehicles traveling on unpaved roads are a familiar sight in rural areas of the United States. When a vehicle travels an unpaved road, the force of the wheels on the road surface causes pulverization of surface material. Particles are lifted and dropped from the rolling wheels, and the road surface is exposed to strong air currents in turbulent shear with the surface. The turbulent wake behind the vehicle continues to act on the road surface after the vehicle has passed.

11.2.1.2 Emissions and Correction Parameters

The quantity of dust emissions from a given segment of unpaved road varies linearly with the volume of traffic. Also, field investigations have shown that emissions depend on correction parameters (average vehicle speed, average vehicle weight, average number of wheels per vehicle, road surface texture and road surface moisture) that characterize the condition of a particular road and the associated vehicle traffic.[1-4]

Dust emissions from unpaved roads have been found to vary in direct proportion to the fraction of silt (particles smaller than 75 micrometers in diameter) in the road surface material.[1] The silt fraction is determined by measuring the proportion of loose dry surface dust that passes a 200 mesh screen, using the ASTM-C-136 method. Table 11.2.1-1 summarizes measured silt values for industrial and rural unpaved roads.

TABLE 11.2.1-1. TYPICAL SILT CONTENT VALUES OF SURFACE MATERIALS ON INDUSTRIAL AND RURAL UNPAVED ROADS[a]

Industry	Road use or surface material	No. of test samples	Silt (%) Range	Silt (%) Mean
Iron and steel production	Plant road	13	4.3 - 13	7.3
Taconite mining and processing	Haul road	12	3.7 - 9.7	5.8
	Service road	8	2.4 - 7.1	4.3
Western surface coal mining	Access road	2	4.9 - 5.3	5.1
	Haul road	21	2.8 - 18	8.4
	Scraper road	10	7.2 - 25	17
	Haul road (freshly graded)	5	18 - 29	24
Rural roads	Gravel	2	12 - 13	12
	Dirt	1		68

[a] References 1-9.

The silt content of a rural dirt road will vary with location, and it should be measured. As a conservative approximation, the silt content of the parent soil in the area can be used. However, tests show that road silt content is normally lower than the surrounding parent soil, because the fines are continually removed by the vehicle traffic, leaving a higher percentage of coarse particles.

Unpaved roads have a hard nonporous surface that usually dries quickly after a rainfall. The temporary reduction in emissions because of precipitation may be accounted for by neglecting emissions on "wet" days [more than 0.254 mm (0.01 in.) of precipitation].

11.2.1.3 Predictive Emission Factor Equations

The following empirical expression may be used to estimate the quantity of size specific particulate emissions from an unpaved road, per vehicle unit of travel, with a rating of A:

$$E = k(1.7) \left(\frac{s}{12}\right) \left(\frac{S}{48}\right) \left(\frac{W}{2.7}\right)^{0.7} \left(\frac{w}{4}\right)^{0.5} \left(\frac{365-p}{365}\right) \quad (\text{kg/VKT}) \qquad (1)$$

$$E = k(5.9) \left(\frac{s}{12}\right) \left(\frac{S}{30}\right) \left(\frac{W}{3}\right)^{0.7} \left(\frac{w}{4}\right)^{0.5} \left(\frac{365-p}{365}\right) \quad (\text{lb/VMT})$$

where: E = emission factor
k = particle size multiplier (dimensionless)
s = silt content of road surface material (%)
S = mean vehicle speed, km/hr (mph)
W = mean vehicle weight, Mg (tons)
w = mean number of wheels
p = number of days with at least 0.254 mm (0.01 in.) of precipitation per year

The particle size multiplier (k) in Equation 1 varies with aerodynamic particle size range as follows:

Aerodynamic Particle Size Multipler
for Equation 1

< 30 μm	< 15 μm	< 10 μm	< 5 μm	< 2.5 μm
0.80	0.57	0.45	0.28	0.16

The number of wet days per year (p) for the geographical area of interest should be determined from local climatic data. Figure 11.2.1-1 gives the geographical distribution of the mean annual number of wet days per year in the United States.

Equation 1 retains the assigned quality rating if applied within the ranges of source conditions that were tested in developing the equation, as follows:

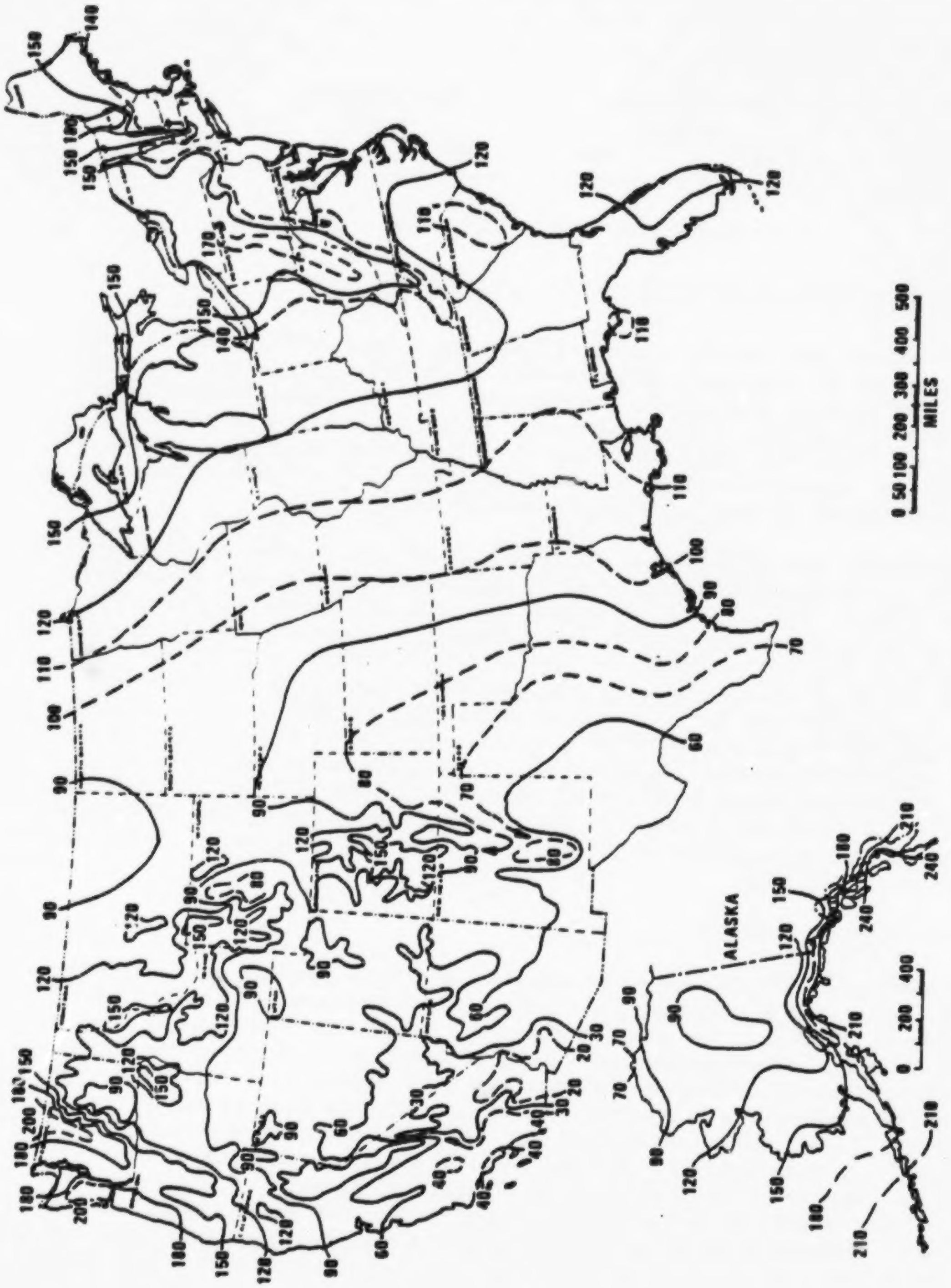

Figure 11.2.1-1. Mean number of days with 0.01 inch or more of precipitation in United States.[10]

Range of Source Conditions for Equation 1

Road surface silt content (%)	Mean vehicle weight		Mean vehicle speed		Mean No. of wheels
	Mg	tons	km/hr	mph	
4.3 - 20	2.7 - 142	3 - 157	21 - 64	13 - 40	4 - 13

Also, to retain the quality rating of Equation 1 applied to a specific unpaved road, it is necessary that reliable correction parameter values for the specific road in question be determined. The field and laboratory procedures for determining road surface silt content are given in Reference 4. In the event that site specific values for correction parameters cannot be obtained, the appropriate mean values from Table 11.2.1-1 may be used, but the quality rating of the equation is reduced to B.

Equation 1 was developed for calculation of annual average emissions, and thus, is to be multiplied by annual source extent in vehicle distance traveled (VDT). Annual average values for each of the correction parameters are to be substituted into the equation. Worst case emissions, corresponding to dry road conditions, may be calculated by setting $p = 0$ in Equation 1 (which is equivalent to dropping the last term from the equation). A separate set of nonclimatic correction parameters and a higher than normal VDT value may also be justified for the worst case averaging period (usually 24 hours). Similarly, to calculate emissions for a 91 day season of the year using Equation 1, replace the term $(365-p)/365$ with the term $(91-p)/91$, and set p equal to the number of wet days in the 91 day period. Also, use appropriate seasonal values for the nonclimatic correction parameters and for VDT.

11.2.1.4 Control Methods

Common control techniques for unpaved roads are paving, surface treating with penetration chemicals, working soil stabilization chemicals into the roadbed, watering, and traffic control regulations. Paving, as a control technique, is often not economically practical. Surface chemical treatment and watering can be accomplished with moderate to low costs, but frequent retreatments are required. Traffic controls such as speed limits and traffic volume restrictions provide moderate emission reductions but may be difficult to enforce. Table 11.2.1-3 shows approximate control efficiencies achievable for each method. Watering, because of the frequency of treatments required, is generally not feasible for public roads and is effectively used only where water and watering equipment are available and where roads are confined to a single site, such as a construction location.

TABLE 11.2.1-3. CONTROL METHODS FOR UNPAVED ROADS[11]

Control method	Approximate control efficiency (%)
Paving	85
Treating surface with penetrating chemicals	50
Working soil stabilizing chemicals into roadbed	50
Speed control[a]	
48 kph (30 mph)	25
32 kph (20 mph)	50
24 kph (15 mph)	63

[a] Based on the assumption that "uncontrolled" speed is typically 64 kph (40 mph). Between 21 and 64 kph (13 and 40 mph), emissions are linearly proportional to vehicle speed (see Equation 1).

References for Section 11.2.1

1. C. Cowherd, *et al.*, *Development of Emission Factors for Fugitive Dust Sources*, EPA-450/3-74-037, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

2. R. J. Dyck and J. J. Stukel, "Fugitive Dust Emissions from Trucks on Unpaved Roads", *Environmental Science and Technology*, *10*(10):1046-1048, October 1976.

3. R. O. McCaldin and K. J. Heidel, "Particulate Emissions from Vehicle Travel over Unpaved Roads", Presented at the 71st Annual Meeting of the Air Pollution Control Association, Houston, TX, June 1978.

4. C. Cowherd, Jr., *et al.*, *Iron and Steel Plant Open Dust Source Fugitive Emission Evaluation*, EPA-600/2-79-103, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1979.

5. R. Bohn, *et al.*, *Fugitive Emissions from Integrated Iron and Steel Plants*, EPA-600/2-78-050, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1978.

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7. C. Cowherd, Jr., and T. Cuscino, Jr., Fugitive Emissions Evaluation, Equitable Environmental Health, Inc., Elmhurst, IL, February 1977.

8. T. Cuscino, et al., Taconite Mining Fugitive Emissions Study, Minnesota Pollution Control Agency, Roseville, MN, June 1979.

9. K. Axetell and C. Cowherd, Jr., Improved Emission Factors for Fugitive Dust from Western Surface Coal Mining Sources, 2 Volumes, EPA Contract No. 68-03-2924, PEDCo Environmental, Inc., Kansas City, MO, July 1981.

10. Climatic Atlas of the United States, U. S. Department of Commerce, Washington, DC, June 1968.

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11.2.2 AGRICULTURAL TILLING

11.2.2.1 General

The two universal objectives of agricultural tilling are the creation of the desired soil structure to be used as the crop seedbed and the eradication of weeds. Plowing, the most common method of tillage, consists of some form of cutting loose, granulating and inverting the soil, and turning under the organic litter. Implements that loosen the soil and cut off the weeds but leave the surface trash in place have recently become more popular for tilling in dryland farming areas.

During a tilling operation, dust particles from the loosening and pulverization of the soil are injected into the atmosphere as the soil is dropped to the surface. Dust emissions are greatest during periods of dry soil and during final seedbed preparation.

11.2.2.2 Emissions and Correction Parameters

The quantity of dust from agricultural tilling is proportional to the area of land tilled. Also, emissions depend on surface soil texture and surface soil moisture content, conditions of a particular field being tilled.

Dust emissions from agricultural tilling have been found to vary directly with the silt content (defined as particles < 75 micrometers in diameter) of the surface soil depth (0 to 10 cm [0 to 4 in.]). The soil silt content is determined by measuring the proportion of dry soil that passes a 200 mesh screen, using ASTM-C-136 method. Note that this definition of silt differs from that customarily used by soil scientists, for whom silt is particles from 2 to 50 micrometers in diameter.

Field measurements[2] indicate that dust emissions from agricultural tilling are not significantly related to surface soil moisture, although limited earlier data had suggested such a dependence.[1] This is now believed to reflect the fact that most tilling is performed under dry soil conditions, as were the majority of the field tests.[1-2]

Available test data indicate no substantial dependence of emissions on the type of tillage implement, if operating at a typical speed (for example, 8 to 10 km/hr [5 to 6 mph]).[1-2]

11.2.2.3 Predictive Emission Factor Equation

The quantity of dust emissions from agricultural tilling, per acre of land tilled, may be estimated with a rating of A or B (see below) using the following empirical expression[2]:

$$E = k(604)(s)^{0.6} \quad \text{(kg/hectare)} \qquad (1)$$

$$E = k(538)(s)^{0.6} \quad \text{(lb/acre)}$$

where: E = emission factor
k = particle size multipler (dimensionless)
s = silt content of surface soil (%)

The particle size multiplier (k) in the equation varies with aerodynamic particle size range as follows:

Aerodynamic Particle Size Multiplier for Equation 1

Total particulate	< 30 μm	< 15 μm	< 10 μm	< 5 μm	< 2.5 μm
1.0	0.33	0.25	0.21	0.15	0.10

Equation 1 is rated A if used to estimate total particulate emissions, and B if used for a specific particle size range. The equation retains its assigned quality rating if applied within the range of surface soil silt content (1.7 to 88 percent) that was tested in developing the equation. Also, to retain the quality rating of Equation 1 applied to a specific agricultural field, it is necessary to obtain a reliable silt value(s) for that field. The sampling and analysis procedures for determining agricultural silt content are given in Reference 2. In the event that a site specific value for silt content cannot be obtained, the mean value of 18 percent may be used, but the quality rating of the equation is reduced by one level.

11.2.2.4 Control Methods[3]

In general, control methods are not applied to reduce emissions from agricultural tilling. Irrigation of fields before plowing will reduce emissions, but in many cases, this practice would make the soil unworkable and would adversely affect the plowed soil's characteristics. Control methods for agricultural activities are aimed primarily at reduction of emissions from wind erosion through such practices as continuous cropping, stubble mulching, strip cropping, applying limited irrigation to fallow fields, building windbreaks, and using chemical stabilizers. No data are available to indicate the effects of these or other control methods on agricultural tilling, but as a practical matter, it may be assumed that emission reductions are not significant.

References for Section 11.2.2

1. C. Cowherd, Jr., et al., Development of Emission Factors for Fugitive Dust Sources, EPA-450/3-74-037, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

2. T. A. Cuscino, Jr., et al., The Role of Agricultural Practices in Fugitive Dust Emissions, California Air Resources Board, Sacramento, CA, June 1981.

3. G. A Jutze, et al., Investigation of Fugitive Dust - Sources Emissions And Control, EPA-450/3-74-036a, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

11.2.3 AGGREGATE HANDLING AND STORAGE PILES

11.2.3.1 General

Inherent in operations that use minerals in aggregate form is the maintenance of outdoor storage piles. Storage piles are usually left uncovered, partially because of the need for frequent material transfer into or out of storage.

Dust emissions occur at several points in the storage cycle, during material loading onto the pile, during disturbances by strong wind currents, and during loadout from the pile. The movement of trucks and loading equipment in the storage pile area is also a substantial source of dust.

11.2.3.2 Emissions and Correction Parameters

The quantity of dust emissions from aggregate storage operations varies with the volume of aggregate passing through the storage cycle. Also, emissions depend on three correction parameters that characterize the condition of a particular storage pile: age of the pile, moisture content and proportion of aggregate fines.

When freshly processed aggregate is loaded onto a storage pile, its potential for dust emissions is at a maximum. Fines are easily disaggregated and released to the atmosphere upon exposure to air currents from aggregate transfer itself or high winds. As the aggregate weathers, however, potential for dust emissions is greatly reduced. Moisture causes aggregation and cementation of fines to the surfaces of larger particles. Any significant rainfall soaks the interior of the pile, and the drying process is very slow.

Field investigations have shown that emissions from aggregate storage operations vary in direct proportion to the percentage of silt (particles < 75 µm in diameter) in the aggregate material.[1 3] The silt content is determined by measuring the proportion of dry aggregate material that passes through a 200 mesh screen, using ASTM-C-136 method. Table 11.2.3-1 summarizes measured silt and moisture values for industrial aggregate materials.

11.2.3.3 Predictive Emission Factor Equations

Total dust emissions from aggregate storage piles are contributions of several distinct source activities within the storage cycle:

1. Loading of aggregate onto storage piles (batch or continuous drop operations).
2. Equipment traffic in storage area.
3. Wind erosion of pile surfaces and ground areas around piles.
4. Loadout of aggregate for shipment or for return to the process stream (batch or continuous drop operations).

TABLE 11.2.3-1. TYPICAL SILT AND MOISTURE CONTENT VALUES OF MATERIALS AT VARIOUS INDUSTRIES

Industry	Material	Silt (%)			Moisture (%)		
		No. of test samples	Range	Mean	No. of test samples	Range	Mean
Iron and steel production[a]	Pellet ore	10	1.4 - 13	4.9	8	0.64 - 3.5	2.1
	Lump ore	9	2.8 - 19	9.5	6	1.6 - 8.1	5.4
	Coal	7	2 - 7.7	5	6	2.8 - 11	4.8
	Slag	3	3 - 7.3	5.3	3	0.25 - 2.2	0.92
	Flue dust	2	14 - 23	18.0	0	NA	NA
	Coke breeze	1		5.4	1		6.4
	Blended ore	1		15.0	1		6.6
	Sinter	1		0.7	0	NA	NA
	Limestone	1		0.4	0	NA	NA
Stone quarrying and processing[b]	Crushed limestone	2	1.3 - 1.9	1.6	2	0.3 - 1.1	0.7
Taconite mining and processing[c]	Pellets	9	2.2 - 5.4	3.4	7	0.05 - 2.3	0.96
	Tailings	2	NA	11.0	1		0.35
Western surface coal mining[d]	Coal	15	3.4 - 16	6.2	7	2.8 - 20	6.9
	Overburden	15	3.8 - 15	7.5	0	NA	NA
	Exposed ground	3	5.1 - 21	15.0	3	0.8 - 6.4	3.4

[a] References 2-5. NA = not applicable.
[b] Reference 1.
[c] Reference 6.
[d] Reference 7.

Adding aggregate material to a storage pile or removing it usually involves dropping the material onto a receiving surface. Truck dumping on the pile or loading out from the pile to a truck with a front end loader are examples of batch drop operations. Adding material to the pile by a conveyor stacker is an example of a continuous drop operation.

The quantity of particulate emissions generated by a batch drop operation, per ton of material transferred, may be estimated, with a rating of C, using the following empirical expression[2]:

$$E = k(0.00090)\ \frac{\left(\frac{s}{5}\right)\left(\frac{U}{2.2}\right)\left(\frac{H}{1.5}\right)}{\left(\frac{M}{2}\right)^{2}\left(\frac{Y}{4.6}\right)^{0.33}}\quad \text{(kg/Mg)} \qquad (1)$$

$$E = k(0.0018)\ \frac{\left(\frac{s}{5}\right)\left(\frac{U}{5}\right)\left(\frac{H}{5}\right)}{\left(\frac{M}{2}\right)^{2}\left(\frac{Y}{6}\right)^{0.33}}\quad \text{(lb/ton)}$$

where: E = emission factor
k = particle size multipler (dimensionless)
s = material silt content (%)
U = mean wind speed, m/s (mph)
H = drop height, m (ft)
M = material moisture content (%)
Y = dumping device capacity, m^3 (yd^3)

The particle size multipler (k) for Equation 1 varies with aerodynamic particle size, shown in Table 11.2.3-2.

TABLE 11.2.3-2. AERODYNAMIC PARTICLE SIZE MULTIPLIER (k) FOR EQUATIONS 1 AND 2

Equation	< 30 µm	< 15 µm	< 10 µm	< 5 µm	< 2.5 µm
Batch drop	0.73	0.48	0.36	0.23	0.13
Continuous drop	0.77	0.49	0.37	0.21	0.11

The quantity of particulate emissions generated by a continuous drop operation, per ton of material transferred, may be estimated, with a rating of C, using the following empirical expression[3]:

$$E = k(0.00090)\ \frac{\left(\frac{s}{5}\right)\left(\frac{U}{2.2}\right)\left(\frac{H}{3.0}\right)}{\left(\frac{M}{2}\right)^2}\ \ (\text{kg/Mg}) \qquad (2)$$

$$E = k(0.0018)\ \frac{\left(\frac{s}{5}\right)\left(\frac{U}{5}\right)\left(\frac{H}{10}\right)}{\left(\frac{M}{2}\right)^2}\ \ (\text{lb/ton})$$

where: E = emission factor
k = particle size multiplier (dimensionless)
s = material silt content (%)
U = mean wind speed, m/s (mph)
H = drop height, m (ft)
M = material moisture content (%)

The particle size multiplier (k) for Equation 2 varies with aerodynamic particle size, as shown in Table 11.2.3-2.

Equations 1 and 2 retain the assigned quality rating if applied within the ranges of source conditions that were tested in developing the equations, as given in Table 11.2.3-3. Also, to retain the quality ratings of Equations 1 or 2 applied to a specific facility, it is necessary that reliable correction parameters be determined for the specific sources of interest. The field and laboratory procedures for aggregate sampling are given in Reference 3. In the event that site specific values for correction parameters cannot be obtained, the appropriate mean values from Table 11.2.3-1 may be used, but in that case, the quality ratings of the equations are reduced by one level.

TABLE 11.2.3-3. RANGES OF SOURCE CONDITIONS FOR EQUATIONS 1 AND 2[a]

Equation	Silt content (%)	Moisture content (%)	Dumping capacity		Drop height	
			m^3	yd^3	m	ft
Batch drop	1.3 - 7.3	0.25 - 0.70	2.10 - 7.6	2.75 - 10	NA	NA
Continuous drop	1.4 - 19	0.64 - 4.8	NA	NA	1.5 - 12	4.8 - 39

[a] NA = not applicable.

For emissions from equipment traffic (trucks, front end loaders, dozers, etc.) traveling between or on piles, it is recommended that the equations for vehicle traffic on unpaved surfaces be used (see Section 11.2.1). For vehicle travel between storage piles, the silt value(s) for the areas among the piles (which may differ from the silt values for the stored materials) should be used.

For emissions from wind erosion of active storage piles, the following total suspended particulate (TSP) emission factor equation is recommended:

$$E = 1.9 \left(\frac{s}{1.5}\right) \left(\frac{365-p}{235}\right) \left(\frac{f}{15}\right) \text{ (kg/day/hectare)} \qquad (3)$$

$$E = 1.7 \left(\frac{s}{1.5}\right) \left(\frac{365-p}{235}\right) \left(\frac{f}{15}\right) \text{ (lb/day/acre)}$$

where:
- E = total suspended particulate emission factor
- s = silt content of aggregate (%)
- p = number of days with ≧ 0.25 mm (0.01 in.) of precipitation per year
- f = percentage of time that the unobstructed wind speed exceeds 5.4 m/s (12 mph) at the mean pile height

The coefficient in Equation 3 is taken from Reference 1, based on sampling of emissions from a sand and gravel storage pile area during periods when transfer and maintenance equipment was not operating. The factor from Test Report 1, expressed in mass per unit area per day, is more reliable than the factor expressed in mass per unit mass of material placed in storage, for reasons stated in that report. Note that the coefficient has been halved to adjust for the estimate that the wind speed through the emission layer at the test site was one half of the value measured above the top of the piles. The other terms in this equation were added to correct for silt, precipitation and frequency of high winds, as discussed in Reference 2. Equation 3 is rated C for application in the sand and gravel industry and D for other industries.

Worst case emissions from storage pile areas occur under dry windy conditions. Worst case emissions from materials handling (batch and continuous drop) operations may be calculated by substituting into Equations 1 and 2 appropriate values for aggregate material moisture content and for anticipated wind speeds during the worst case averaging period, usually 24 hours. The treatment of dry conditions for vehicle traffic (Section 11.2.1) and for wind erosion (Equation 3), centering around parameter p, follows the methodology described in Section 11.2.1. Also, a separate set of nonclimatic correction parameters and source extent values corresponding to higher than normal storage pile activity may be justified for the worst case averaging period.

11.2.3.4 Control Methods

Watering and chemical wetting agents are the principal means for control of aggregate storage pile emissions. Enclosure or covering of inactive piles to reduce wind erosion can also reduce emissions. Watering is useful mainly to reduce emissions from vehicle traffic in the storage pile area. Watering of the storage piles themselves typically has only a very temporary slight effect on total emissions. A much more effective technique is to apply chemical wetting agents for better wetting of fines and longer retention of the moisture film. Continuous chemical treatment of material loaded onto piles, coupled with watering or treatment of roadways, can reduce total particulate emissions from aggregate storage operations by up to 90 percent.[8]

References for Section 11.2.3

1. C. Cowherd, Jr., et al., Development of Emission Factors for Fugitive Dust Sources, EPA-450/3-74-037, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

2. R. Bohn, et al., Fugitive Emissions from Integrated Iron and Steel Plants, EPA-600/2-78-050, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1978.

3. C. Cowherd, Jr., et al., Iron and Steel Plant Open Dust Source Fugitive Emission Evaluation, EPA-600/2-79-103, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1979.

4. R. Bohn, Evaluation of Open Dust Sources in the Vicinity of Buffalo, New York, U. S. Environmental Protection Agency, New York, NY, March 1979.

5. C. Cowherd, Jr., and T. Cuscino, Jr., Fugitive Emissions Evaluation, Equitable Environmental Health, Inc., Elmhurst, IL, February 1977.

6. T. Cuscino, et al., Taconite Mining Fugitive Emissions Study, Minnesota Pollution Control Agency, Roseville, MN, June 1979.

7. K. Axetell and C. Cowherd, Jr., Improved Emission Factors for Fugitive Dust from Western Surface Coal Mining Sources, 2 Volumes, EPA Contract No. 68-03-2924, PEDCo Environmental, Inc., Kansas City, MO, July 1981.

8. G. A. Jutze, et al., Investigation of Fugitive Dust Sources Emissions and Control, EPA-450/3-74-036a, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

11.2.6 INDUSTRIAL PAVED ROADS

11.2.6.1 General

Various field studies have indicated that dust emissions from industrial paved roads are a major component of atmospheric particulate matter in the vicinity of industrial operations. Industrial traffic dust has been found to consist primarily of mineral matter, mostly tracked or deposited onto the roadway by vehicle traffic itself when vehicles enter from an unpaved area or travel on the shoulder of the road, or when material is spilled onto the paved surface from haul truck traffic.

11.2.6.2 Emissions and Correction Parameters

The quantity of dust emissions from a given segment of paved road varies linearly with the volume of traffic. In addition, field investigations have shown that emissions depend on correction parameters (road surface silt content, surface dust loading and average vehicle weight) of a particular road and associated vehicle traffic.[1-2]

Dust emissions from industrial paved roads have been found to vary in direct proportion to the fraction of silt (particles < 75 μm in diameter) in the road surface material.[1-2] The silt fraction is determined by measuring the proportion of loose dry surface dust that passes a 200 mesh screen, using the ASTM-C-136 method. In addition, it has also been found that emissions vary in direct proportion to the surface dust loading.[1-2] The road surface dust loading is that loose material which can be collected by vacuuming and broom sweeping the traveled portion of the paved road. Table 11.2.6-1 summarizes measured silt and loading values for industrial paved roads.

TABLE 11.2.6-1. TYPICAL SILT CONTENT AND LOADING VALUES FOR PAVED ROADS AT IRON AND STEEL PLANTS[a]

		Silt (%)		Loading			
				Range		Mean	
Industry	Travel lanes	Range	Mean	kg/km	lb/mi	kg/km	lb/mi
Iron and steel production	2	1.1 - 13	5.9	18 - 4,800	65 - 17,000	760	2,700

[a] References 1-3. Based on nine test samples.

11.2.6.3 Predictive Emission Factor Equation

The quantity of particulate emissions generated by vehicle traffic on dry industrial paved roads, per vehicle mile traveled, may be estimated, with a rating of B or D (see below), using the following empirical expression:

$$E = k(0.025)I \left(\frac{4}{n}\right) \left(\frac{s}{10}\right) \left(\frac{L}{280}\right) \left(\frac{W}{2.7}\right)^{0.7} \quad \text{(kg/VKT)} \qquad (1)$$

$$E = k(0.090)I \left(\frac{4}{n}\right) \left(\frac{s}{10}\right) \left(\frac{L}{1,000}\right) \left(\frac{W}{3}\right)^{0.7} \quad \text{(lb/VMT)}$$

where:
E = emission factor
k = particle size multiplier (dimensionless) (see below)
I = industrial augmentation factor (dimensionless) (see below)
n = number of traffic lanes
s = surface material silt content (%)
L = surface dust loading, kg/km (lb/mile) (see below)
W = average vehicle weight, Mg (tons)

The particle size multipler (k) above varies with aerodynamic size range as follows:

Aerodynamic Particle Size Multiplier (k)
for Equation 1

< 30 µm	< 15 µm	< 10 µm	< 5 µm	< 2.5 µm
0.86	0.64	0.51	0.32	0.17

To determine particulate emissions for a specific particle size range, use the appropriate value of k shown above.

The industrial road augmentation factor (I) in the equation takes into account higher emissions from industrial roads than from urban roads. I = 7.0 for an industrial roadway which traffic enters from unpaved areas. I = 3.5 for an industrial roadway with unpaved shoulders. I = 1.0 for cases in which traffic does not travel unpaved areas. A value of I between 1.0 and 7.0 should be used in the equation which best represents conditions for paved roads at a certain industrial facility.

The equation retains the quality rating of B if applied to vehicles traveling entirely on paved surfaces (I = 1.0) and if applied within the range of source conditions that were tested in developing the equation as follows:

Silt content (%)	Surface loading		No. of lanes	Vehicle weight	
	kg/km	lb/mile		Mg	tons
5.1 - 92	42.0 - 2,000	149 - 7,100	2 - 4	2.7 - 12	3 - 13

If I > 1.0, the rating of the equation drops to D because of the arbitrariness in the guidelines for estimating I.

Also, to retain the quality ratings of Equation 1 applied to a specific industrial paved road, it is necessary that reliable correction parameter values for the specific road in question be determined. The field and laboratory procedures for determining surface material silt content and surface dust loading are given in Reference 2. In the event that site specific values for correction parameters cannot be obtained, the appropriate mean values from Table 11.2.6-1 may be used, but the quality ratings of the equation are reduced by one level.

References for Section 11.2.6

1. R. Bohn, et al., Fugitive Emissions from Integrated Iron and Steel Plants, EPA-600/2-78-050, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1978.

2. C. Cowherd, Jr., et al., Iron and Steel Plant Open Dust Source Fugitive Emission Evaluation, EPA-600/2-79-103, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1979.

3. R. Bohn, Evaluation of Open Dust Sources in the Vicinity of Buffalo, New York, U. S. Environmental Protection Agency, New York, NY, March 1979.

SOME USEFUL WEIGHTS AND MEASURES

grain	0.002	ounces	pound (troy)	12	ounces
gram	0.04	ounces	ton (short)	2000	pounds
ounce	28.35	grams	ton (long)	2240	pounds
kilogram	2.21	pounds	ton (metric)	2200	pounds
pound	0.45	kilograms	ton (shipping)	40	feet^3

centimeter	0.39	inches
inch	2.54	centimeters
foot	30.48	centimeters
meter	1.09	yards
yard	0.91	meters
mile	1.61	kilometers

centimeter^2	0.16	inches^2	centimeter^3	0.061	inches^3
inch^2	6.45	centimeters^2	inch^3	16.39	centimeters^3
foot^2	0.09	meters^2	foot^3	283.17	centimeters^3
meter^2	1.2	yards^2	foot^3	1728	inches^3
yard^2	0.84	meters^2	meter^3	1.31	yards^3
mile^2	2.59	kilometers^2	yard^3	0.77	meters^3

cord	128	feet^3	gallon (U.S.)	231	inches^3
cord	4	meters^3	barrel	31.5	gallons
peck	8	quarts	hogshead	2	barrels
bushel (dry)	4	pecks	township	36	miles^2
bushel	2150.4	inches^3	hectare	2.5	acres

MISCELLANEOUS DATA

One cubic foot of anthracite coal weighs about 53 pounds.

One cubic foot of bituminous coal weighs from 47 to 50 pounds.

One ton of coal is equivalent to two cords of wood for steam purposes.

A gallon of water (U.S. Standard) weighs 8.33 lbs. and contains 231 cubic inches.

There are 9 square feet of heating surface to each square foot of grate surface.

A cubic foot of water contains 7.5 gallons and 1728 cubic inches, and weighs 62.5 lbs.

Each nominal horsepower of a boiler requires 30 to 35 lbs. of water per hour.

A horsepower is equivalent to raising 33,000 pounds one foot per minute, or 550 pounds one foot per second.

To find the pressure in pounds per square inch of column of water, multiply the height of the column in feet by 0.434.

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TYPICAL PARAMETERS OF VARIOUS FUELS[a]

Type of Fuel	Heating Value		Sulfur	Ash
	kcal	BTU	% (by weight)	% (by weight)
Solid Fuels				
Bituminous Coal	7,200/kg	13,000/lb	0.6-5.4	4-20
Anthracite Coal	6,810/kg	12,300/lb	0.5-1.0	7.0-16.0
Lignite (@ 35% moisture)	3,990/kg	7,200/lb	0.7	6.2
Wood (@ 40% moisture)	2,880/kg	5,200/lb	N	1-3
Bagasse (@ 50% moisture)	2,220/kg	4,000/lb	N	1-2
Bark (@ 50% moisture)	2,492/kg	4,500/lb	N	1-3[b]
Coke, Byproduct	7,380/kg	13,300/lb	0.5-1.0	0.5-5.0
Liquid Fuels				
Residual Oil	$9.98 \times 10^6/m^3$	150,000/gal	0.5-4.0	0.05-0.1
Distillate Oil	$9.30 \times 10^6/m^3$	140,000/gal	0.2-1.0	N
Diesel	$9.12 \times 10^6/m^3$	137,000/gal	0.4	N
Gasoline	$8.62 \times 10^6/m^3$	130,000/gal	0.03-0.04	N
Kerosene	$8.32 \times 10^6/m^3$	135,000/gal	0.02-0.05	N
Liquid Petroleum Gas	$6.25 \times 10^6/m^3$	94,000/gal	N	N
Gaseous Fuels				
Natural Gas	$9,341/nm^3$	1,050/SCF	N	N
Coke Oven Gas	$5,249/nm^3$	590/SCF	0.5-2.0	N
Blast Furnace Gas	$890/nm^3$	100/SCF	N	N

[a] N = negligible.

[b] Ash content may be considerably higher when sand, dirt, etc. are present.

DENSITIES OF SELECTED SUBSTANCES

Substance	Density	
Fuels		
Crude Oil	874 kg/m^3	7.3 lb/gal
Residual Oil	944 kg/m^3	7.88 lb/gal
Distillate Oil	845 kg/m^3	7.05 lb/gal
Gasoline	739 kg/m^3	6.17 lb/gal
Natural Gas	673 kg/m^3	1 lb/23.8 ft^3
Butane	579 kg/m^3	4.84 lb/gal (liquid)
Propane	507 kg/m^3	4.24 lb/gal (liquid)
Wood (Air dried)		
Elm	561 kg/m^3	35 lb/ft^3
Fir, Douglas	513 kg/m^3	32 lb/ft^3
Fir, Balsam	400 kg/m^3	25 lb/ft^3
Hemlock	465 kg/m^3	29 lb/ft^3
Hickory	769 kg/m^3	48 lb/ft^3
Maple, Sugar	689 kg/m^3	43 lb/ft^3
Maple, White	529 kg/m^3	33 lb/ft^3
Oak, Red	673 kg/m^3	42 lb/ft^3
Oak, White	769 kg/m^3	48 lb/ft^3
Pine, Southern	641 kg/m^3	40 lb/ft^3
Agricultural Products		
Corn	25.4 kg/bu	56 lb/bu
Milo	25.4 kg/bu	56 lb/bu
Oats	14.5 kg/bu	32 lb/bu
Barley	21.8 kg/bu	48 lb/bu
Wheat	27.2 kg/bu	60 lb/bu
Cotton	226 kg/bale	500 lb/bale
Mineral Products		
Brick	2.95 kg/brick	6.5 lb/brick
Cement	170 kg/bbl	375 lb/bbl
Cement	1483 kg/m^3	2500 lb/yd^3
Concrete	2373 kg/m^3	4000 lb/yd^3
Glass, Common	2595 kg/m^3	162 lb/ft^3
Gravel, Dry Packed	1600-1920 kg/m^3	100-120 lb/ft^3
Gravel, Wet	2020 kg/m^3	126 lb/ft^3
Gypsum, Calcined	880-960 kg/m^3	55-60 lb/ft^3
Lime, Pebble	850-1025 kg/m^3	53-64 lb/ft^3
Sand, Gravel (Dry, loose)	1440-1680 kg/m^3	90-105 lb/ft^3

CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS

AIRBORNE PARTICULATE MATTER

To convert from	To	Multiply by
Milligrams/cu m	Grams/cu ft	283.2×10^{-6}
	Grams/cu m	0.001
	Micrograms/cu m	1000.0
	Micrograms/cu ft	28.32
	Pounds/1000 cu ft	62.43×10^{-6}
Grams/cu ft	Milligrams/cu m	35.3145×10^{3}
	Grams/cu m	35.314
	Micrograms/cu m	35.314×10^{6}
	Micrograms/cu ft	1.0×10^{6}
	Pounds/1000 cu ft	2.2046
Grams/cu m	Milligrams/cu m	1000.0
	Grams/cu ft	0.02832
	Micrograms/cu m	1.0×10^{6}
	Micrograms/cu ft	28.317×10^{3}
	Pounds/1000 cu ft	0.06243
Micrograms/cu m	Milligrams/cu m	0.001
	Grams/cu ft	28.317×10^{-9}
	Grams/cu m	1.0×10^{-6}
	Micrograms/cu ft	0.02832
	Pounds/1000 cu ft	62.43×10^{-9}
Micrograms/cu ft	Milligrams/cu m	35.314×10^{-3}
	Grams/cu ft	1.0×10^{-6}
	Grams/cu m	35.314×10^{-6}
	Micrograms/cu m	35.314
	Pounds/1000 cu ft	2.2046×10^{-6}
Pounds/1000 cu ft	Milligrams/cu m	16.018×10^{3}
	Grams/cu ft	0.35314
	Micrograms/cu m	16.018×10^{6}
	Grams/cu m	16.018
	Micrograms/cu ft	353.14×10^{3}

SAMPLING PRESSURE

To convert from	To	Multiply by
Millimeters of mercury (0°C)	Inches of water (60°F)	0.5358
Inches of mercury (0°C)	Inches of water (60°F)	13.609
Inches of water (60°F)	Millimeters of mercury (0°C)	1.8663
	Inches of mercury (0°C)	73.48×10^{-3}

CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS

ATMOSPHERIC GASES

To convert from	To	Multiply by
Milligrams/cu m	Micrograms/cu m	1000.0
	Micrograms/liter	1.0
	Ppm by volume (20°C)	$\frac{24.04}{M}$
	Ppm by weight	0.8347
	Pounds/cu ft	62.43×10^{-9}
Micrograms/cu m	Milligrams/cu m	0.001
	Micrograms/liter	0.001
	Ppm by volume (20°C)	$\frac{0.02404}{M}$
	Ppm by weight	834.7×10^{-6}
	Pounds/cu ft	62.43×10^{-12}
Micrograms/liter	Milligrams/cu m	1.0
	Micrograms/cu m	1000.0
	Ppm by volume (20°C)	$\frac{24.04}{M}$
	Ppm by weight	0.8347
	Pounds/cu ft	62.43×10^{-9}
Ppm by volume (20°C)	Milligrams/cu m	$\frac{M}{24.04}$
	Micrograms/cu m	$\frac{M}{0.02404}$
	Micrograms/liter	$\frac{M}{24.04}$
	Ppm by weight	$\frac{M}{28.8}$
	Pounds/cu ft	$\frac{M}{385.1 \times 10^{6}}$
Ppm by weight	Milligrams/cu m	1.198
	Micrograms/cu m	1.198×10^{-3}
	Micrograms/liter	1.198
	Ppm by volume (20°C)	$\frac{28.8}{M}$
	Pounds/cu ft	7.48×10^{-6}
Pounds/cu ft	Milligrams/cu m	16.018×10^{6}
	Micrograms/cu m	16.018×10^{9}
	Micrograms/liter	16.018×10^{6}
	Ppm by volume (20°C)	$\frac{385.1 \times 10^{6}}{M}$
	Ppm by weight	133.7×10^{3}

M = Molecular weight of gas.

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CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS

VELOCITY

To convert from	To	Multiply by
Meters/sec	Kilometers/hr	3.6
	Feet/sec	3.281
	Miles/hr	2.237
Kilometers/hr	Meters/sec	0.2778
	Feet/sec	0.9113
	Miles/hr	0.6214
Feet/sec	Meters/sec	0.3048
	Kilometers/hr	1.09728
	Miles/hr	0.6818
Miles/hr	Meters/sec	0.4470
	Kilometers/hr	1.6093
	Feet/sec	1.4667

ATMOSPHERIC PRESSURE

To convert from	To	Multiply by
Atmospheres	Millimeters of mercury	760.0
	Inches of mercury	29.92
	Millibars	1013.2
Millimeters of mercury	Atmospheres	1.316×10^{-3}
	Inches of mercury	39.37×10^{-3}
	Millibars	1.333
Inches of mercury	Atmospheres	0.03333
	Millimeters of mercury	25.4005
	Millibars	33.35
Millibars	Atmospheres	0.00987
	Millimeters of mercury	0.75
	Inches of mercury	0.30

VOLUME EMISSIONS

To convert from	To	Multiply by
Cubic m/min	Cubic ft/min	35.314
Cubic ft/min	Cubic m/min	0.0283

BOILER CONVERSION FACTORS

1 Megawatt = 10.5×10^6 BTU/hr
(8 to 14×10^6 BTU/hr)

1 Megawatt = 8×10^3 lb steam/hr
(6 to 11×10^3 lb steam/hr)

1 BHP = 34.5 lb steam/hr

1 BHP = 45×10^3 BTU/hr
(40 to 50×10^3 BTU/hr)

1 lb steam/hr = 1.4×10^3 BTU/hr
(1.2 to 1.7×10^3 BTU/hr)

NOTES: In the relationships,

Megawatt is the net electric power production of a steam electric power plant.

BHP is boiler horsepower.

Lb steam/hr is the steam production rate of the boiler.

BTU/hr is the heat input rate to the boiler (based on the gross or high heating value of the fuel burned).

For less efficient (generally older and/or smaller) boiler operations, use the higher values expressed. For more efficient operations (generally newer and/or larger), use the lower vlaues.

VOLUME	cu. in.	ml.	liters	ounces (U. S. fl.)	gallons (U. S.)	barrels (U. S.)	cu. ft.
Cubic inches	....	16.3868	.0163868	0.5541	4.3290×10^{-3}	1.37429×10^{-4}	5.78704×10^{-4}
Milliliters	0.061024	....	0.001	0.03381	2.6418×10^{-4}	8.387×10^{-6}	3.5316×10^{-5}
Liters	61.024	1000	....	33.8147	0.26418	8.387×10^{-3}	0.035316
Ounces (U. S. fl.)	1.80469	29.5729	0.029573	....	7.8125×10^{-3}	2.48×10^{-4}	1.0443×10^{-3}
Gallons (U. S.)*..	231	3785.3	3.7853	128	....	0.031746	0.13368
Barrels (U. S.)...	7276.5	1.1924×10^5	119.2369	4032.0	31.5	....	4.2109
Cubic feet	1728	2.8316×10^4	28.316	957.568	7.481	0.23743	....

[1] U. S. gallon of water at 16.7°C (62°F) weighs 3.780 kg. or 8.337 pounds (avoir.)

MASS	grams	kilograms	ounces (avoir.)	pounds (avoir.)	grains	tons (U. S.)	milligrams
Grams	....	0.001	3.527×10^{-2}	2.205×10^{-3}	15.432	1.102×10^{-6}	1000
Kilograms	1000	....	35.274	2.2046	15432	1.102×10^{-3}	1×10^6
Ounces (avoir.)...	28.350	0.028350	....	0.0625	437.5	3.125×10^{-5}	2.8350×10^4
Pounds (avoir.)*..	453.59	0.45359	16.0	....	7000	5.0×10^{-4}	4.5359×10^5
Grains	0.06480	6.480×10^{-5}	2.286×10^{-3}	1.429×10^{-4}	....	7.142×10^{-8}	64.799
Tons (U. S.)	9.072×10^5	907.19	3.200×10^4	2000	1.4×10^7	....	9.0718×10^8
Milligrams	0.001	1×10^{-6}	3.527×10^{-5}	2.205×10^{-6}	0.015432	1.102×10^{-9}	....

*Mass of 27.692 cubic inches water weighed in air at 4.0°C, 760 mm mercury pressure.

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WORK AND ENERGY	g. cal.	kg. cal.	ergs	Joules	BTU	ft. lb.	kg. meters	L-Atm	HP Hours	ft. poundals	KWH	WH
Gram Calories (mean)...........	....	0.001	$4.186x10^{7}$	4.186	$3.9680x10^{-3}$	3.0874	0.42685	0.041311	$1.5593x10^{-6}$	99.334	$1.1628x10^{-6}$	$1.1628x10^{-3}$
Kilogram Calories.	1000	....	$4.186x10^{10}$	4186	3.9680	3087.4	426.85	41.311	$1.5593x10^{-3}$	99334	$1.1628x10^{-3}$	1.1628
Ergs	$2.3889x10^{-8}$	$2.3889x10^{-11}$	....	$1x10^{-7}$	$9.4805x10^{-11}$	$7.3756x10^{-8}$	$1.0197x10^{-8}$	$9.8689x10^{-10}$	$3.7251x10^{-14}$	$2.3730x10^{-6}$	$2.7778x10^{-14}$	$2.7778x10^{-11}$
Joules	0.23889	$2.3889x10^{-4}$	$1x10^{7}$	....	$9.4805x10^{-4}$	0.73756	0.10197	$9.8689x10^{-3}$	$3.7251x10^{-7}$	23.730	$2.7778x10^{-7}$	$2.7778x10^{-4}$
BTU (mean)	251.98	0.25198	$1.0548x10^{10}$	1054.8	....	777.98	107.56	10.409	$3.9292x10^{-4}$	$2.5030x10^{4}$	$2.930x10^{-4}$	0.2930
Foot Pounds	0.32389	$3.2389x10^{-4}$	$1.35582x10^{7}$	1.3558	$1.2854x10^{-3}$	....	0.13825	0.013381	$5.0505x10^{-7}$	32.174	$3.7662x10^{-7}$	$3.7662x10^{-4}$
Kilogram meters ..	2.3427	$2.3427x10^{-3}$	$9.8066x10^{7}$	9.8066	$9.2967x10^{-3}$	7.2330	....	0.096781	$3.6529x10^{-6}$	232.71	$2.7241x10^{-6}$	$2.7241x10^{-3}$
Liter Atmospheres (normal)	24.206	$2.4206x10^{-2}$	$1.0133x10^{9}$	101.328	0.09606	74.735	10.333	....	$3.7745x10^{-5}$	2404.5	$2.8164x10^{-5}$	$2.8164x10^{-2}$
Horsepower Hours .	$6.4130x10^{5}$	641.30	$2.6845x10^{13}$	$2.6845x10^{6}$	2454.0	$1.9800x10^{6}$	$2.7374x10^{5}$	26494	....	$6.3705x10^{7}$	0.7457	745.7
Foot poundals	0.010067	$10.067x10^{-6}$	$4.21402x10^{5}$	0.04214	$3.9952x10^{-5}$	0.031081	$4.2972x10^{-3}$	$4.1558x10^{-4}$	$1.5697x10^{-8}$	....	$1.17055x10^{-8}$	$1.17055x10^{-5}$
Kilowatt Hours ...	$8.6001x10^{5}$	860.01	$3.6000x10^{13}$	$3.6000x10^{6}$	3413.0	$2.6552x10^{6}$	$3.6709x10^{-5}$	$3.5529x10^{6}$	1.3440	$8.5430x10^{7}$	....	1000
Watt Hours	860.01	0.86001	$3.6000x10^{10}$	3600	3.4130	2655.3	367.09	$3.5529x10^{3}$	$1.3410x10^{-3}$	$8.5430x10^{1}$	0.001	....

POWER	watts	kw	ft. lb./sec	erg/sec	BTU/min	g. cm/sec	kg. cal/min	HP	Lumens	Joules/sec	BTU/hr.
Watts	....	0.001	0.73756	1×10^{7}	0.056884	1.0197×10^{4}	0.01433	1.341×10^{-3}	668	1	3.41304
Kilowatts	1000	....	737.56	1×10^{10}	56.884	1.0197×10^{7}	14.3334	1.3410	6.68×10^{5}	1000	3413.04
Foot pounds per second..........	1.35582	1.3558×10^{-3}	....	1.3558×10^{7}	0.077124	1.3826×10^{4}	0.019433	1.8182×10^{-3}	906.28	1.3558	4.6274
Ergs per second ..	1×10^{-7}	1×10^{-10}	7.3756×10^{-8}	....	5.688×10^{-9}	1.0197×10^{-3}	1.4333×10^{-9}	1.3410×10^{-10}	6.6845×10^{-5}	1×10^{-7}	3.4130×10^{-7}
BTU* per minute ..	17.580	0.017580	12.9600	1.7580×10^{8}	....	1.7926×10^{5}	0.2520	0.023575	11751	17.580	60
Gram Centimeters per second	9.8067×10^{-5}	9.8067×10^{-8}	7.2330×10^{-5}	980.665	5.5783×10^{-6}	....	1.4056×10^{-6}	1.3151×10^{-7}	0.065552	9.8067×10^{-5}	3.3470×10^{-4}
Kilogram colories per minute	69.767	.069767	51.457	6.9770×10^{8}	3.9685	7.1146×10^{5}	....	0.093557	46636	69.769	238.11
Horsepower (U. S.)	745.7	0.7457	550	7.457×10^{9}	42.4176	7.6042×10^{6}	10.688	....	498129	745.7	2545.1
Lumens	1.496×10^{-3}	1.496×10^{-6}	1.0034×10^{-3}	1.496×10^{4}	8.5096×10^{-5}	15.254	2.1437×10^{-5}	2.0061×10^{-6}	....	1.496×10^{-3}	5.1069×10^{-3}
Joules per second	1	0.001	0.73756	1×10^{7}	0.056884	1.0197×10^{4}	0.01433	1.341×10^{-3}	668	....	3.41304
BTU* per hour.....	0.29299	2.9299×10^{-4}	0.21610	2.9299×10^{6}	0.01667	2.9878×10^{3}	4.1997×10^{-3}	3.9291×10^{-4}	195.80	0.29299	....

*British Thermal Units (Mean)